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HUMAN OPERATOR RESPONSE SPEED, FREQUENCY, AND FLEXIBILITY:

A Review, Analysis and Device Demonstration

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SUMMARY

The human operator's manual control speed, frequency and flexibility is limited by his innate characteristics and by the state-of-the-art in manual control technology. The basis of these limitations was reviewed and analyzed and recommendations for overcoming or reducing these limitations were suggested. On the basis of these suggestions a muscle action potential control, simultaneous visual-auditory display device was developed to demonstrate the increase in operator response speed, frequency and flexibility that can accrue from advanced manual control techniques.

In a discrete control situation muscle action potential control was found to increase response speed by approximately 100 ms and simultaneous visual-auditory display was found to reduce response time by an additional 40 ms. In a continuous control situation, muscle action potential control via the facial muscles increased operator response bandwidth across a range of forcing function amplitudes. These results demonstrate the increase in response speed, frequency and flexibility that accrues from use of muscle action potential control and suggests that further development of muscle action potential control devices is warranted.

INTRODUCTION

Modern supersonic aircraft and ultrasonic spacecraft tax the human operator's manual control skills to their utmost. During even the most routine maneuvers the pilot is often required to control several inputs simultaneously with extraordinary speed and precision. The principle advantage of placing the human operator in the control loop of such vehicles is to take advantage of his unique perceptual and cognitive skills. Man's principle shortcoming in complex high speed vehicles is his limited response frequency and flexibility.

The primary purpose of the work herein described was: (a) to develop advanced manual control techniques that increase man's response speed and flexibility, and (b) to demonstrate the feasibility of these techniques via the development of an ultra-quick control-display device that permits freedom of the operator's limbs for other control activities. The initial approach to the problem consisted of review and analysis of the literature relating to man's response limitations. Section I of this report represents the outcome of this work. Several of the control-display techniques suggested by the review and analysis were evaluated in a disjunctive reaction time study which is described in Section II. On the basis of this work an ultra-quick control display device was designed and fabricated. A description of the device appears in Section III. The device was then compared to more conventional control-display devices and the results of the evaluation are reported in Section IV. Conclusions, recommendations and plans for the future appear in the final section.

SECTION I

HUMAN OPERATOR RESPONSE SPEED, FREQUENCY, AND FLEXIBILITY: A REVIEW AND ANALYSIS

HUMAN OPERATOR RESPONSE SPEED, FREQUENCY, AND FLEXIBILITY: A REVIEW AND ANALYSIS

Traditionally, man is placed in a system's control loop when any one or any combination of his sensing, pattern recognition, decision making, and planning ability is unequalled by existing electromechanical devices of comparable cost, weight, and size. In many modern control systems, however, man's uniquely adaptable perceptual and cognitive capabilities are limited by his own response characteristics and by the state-of-the-art in manual control technology. The human operator has a limited response speed, frequency, and flexibility.

The human operator requires time to detect and process input signals, to select and initiate a course of action, and to bring his desired response to completion. These innate lags and delays place an upper limit on operator speed and frequency of response. The human operator's response flexibility (his ability to simultaneously control several inputs) is also limited by his innate characteristics. Man has a limited number of response members, only a few of which can be simultaneously controlled with any precision.

In addition to his innate characteristics, the operator's perceptual and cognitive capabilities are limited by the state-of-the-art in manual control technology. Although they have an innate anatomical and psychophysiological basis, man's response speed, frequency, and flexibility can be improved via advanced manual control technology. However, manual control research has generally overlooked the fact that operator delays can be shortened and bypassed; that the operator can be trained to control response members other than those conventionally employed for manual control; that devices and techniques can be developed to increase operator performance in complex high speed systems.

In the past, human operator response limitations could be ignored because they were critical in only a limited number of control situations. However, with the development of many modern vehicles such as supersonic aircraft and ultrasonic spacecraft, demands are placed on the operator's response speed, frequency, and flexibility during even the most routine maneuvers. High frequency simultaneous control activities tax the operator's response speed and flexibility to the utmost. Operator response limitations can no longer be ignored in the development of manual control systems: An advanced manual control technology must be developed to reduce the response limitations on man's perceptual and cognitive adaptability.

The primary purpose of the ensuing discussion is: (a) to review the factors that limit the operator's speed, frequency, and flexibility of response, (b) to analyze these limitations and suggest a technology for overcoming them, and (c) to review the research relevant to this end.

OPERATOR AND SYSTEM LAGS AND DELAYS[1]

Consider the situation of a pilot bringing his supersonic aircraft out of a cloud formation and finding that his aircraft is on a collision course with another supersonic aircraft. The pilot's course of action and the approximate times to accomplish these activities would be as follows:

- visual acquisition of the other aircraft (at least .3 sec);
- recognition of the impending danger (.6 sec);
- selection of a course of action (.5 sec); and
- initiation of the desired control activity (.3 sec).

From first sighting of the oncoming aircraft to initiation of control activity, approximately 1.7 sec transpires before the aircraft receives any input from the operator. In addition to the operator delays, the aircraft itself has a response time before the pilot's control activity effects course and/ or speed changes. If the two aircraft were 3.4 mi or less apart and traveling at 1,800 mi/hr (a closing rate of 1 mi/sec) neither pilot would have enough time to even begin the maneuver to avoid the impending collision (Ely, Bowen, & Orlansky, 1963). This illustrates the type of problem that can occur when man is within the control loop of complex high speed vehicles.

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[1] The Laplace transfer function for delays is $e^{-\tau s}$ and for first- and second-order lags is $\frac{1}{1+\tau s}$ and $\frac{1}{(1+\tau s)(1+\tau s)}$ respectively, where e is the base of the natural logarithm system, τ is the delay or lag in seconds and s is the Laplace operator.

Figure 1 schematically represents the various delays and lags that can occur within closed loop manual control systems. These lags and delays can be dichotomized into those that are operator and equipment imposed. Operator lags and delays can be categorized as: (a) input acquisition and receptor delays, (b) afferent and efferent neural transmission delays, (c) central process delays, and (d) muscle activation and movement time. In addition to operator lags and delays the system itself is subject to: (a) display lags and delays, and (b) lags and delays occurring in the controlled element or system dynamics. Delays and lags whether operator or system imposed tend to limit the frequency response (response bandwidth) of the control system. The following will discuss the nature, extent, and effect of these lags and delays on manual control system performance.

Operator Delays and Lags

The following analysis is based upon the assumption that man has an innate response time, the variability of which can be reduced by appropriate man-machine interface design and the mean of which can be reduced by bypassing the less critical links in the usual chain of events between the stimulus and the response. A manual control response presupposes receptor stimulation, neural conduction to higher cortical centers, perceptual and cognitive activity at these centers, neural conduction to the musculature, and muscular contraction, all of which are processes that take time. Good displays and controls tend to reduce the variability in response time; however, an additional reduction in operator delays can accrue from shortening or bypassing of some of the operator's inherent delays. Of the operator's inherent delays, only the cognitive and perceptual delays cannot be eliminated from the chain of events between stimulus and response. To eliminate the perceptual and cognitive delays of the operator is tantamount to eliminating the operator himself from the control system since the primary reason for including him is to take advantage of his perceptual and cognitive flexibility. The ensuing analysis focuses on the basis of operator delays and suggests the links in the chain of stimulus and response events that can be shortened or eliminated to minimize operator "innate response time."

Receptor delays. -- Sensory and perceptual delays are a function of the operator's vigilance level, the sense modality stimulated, the form, intensity, quality, and surround of the input signal. Optimum display design requires consideration of these factors to maximize the compatibility of the input with the sensory and perceptual characteristics of the operator. Vigilance factors are reviewed elsewhere (cf: Buckner &

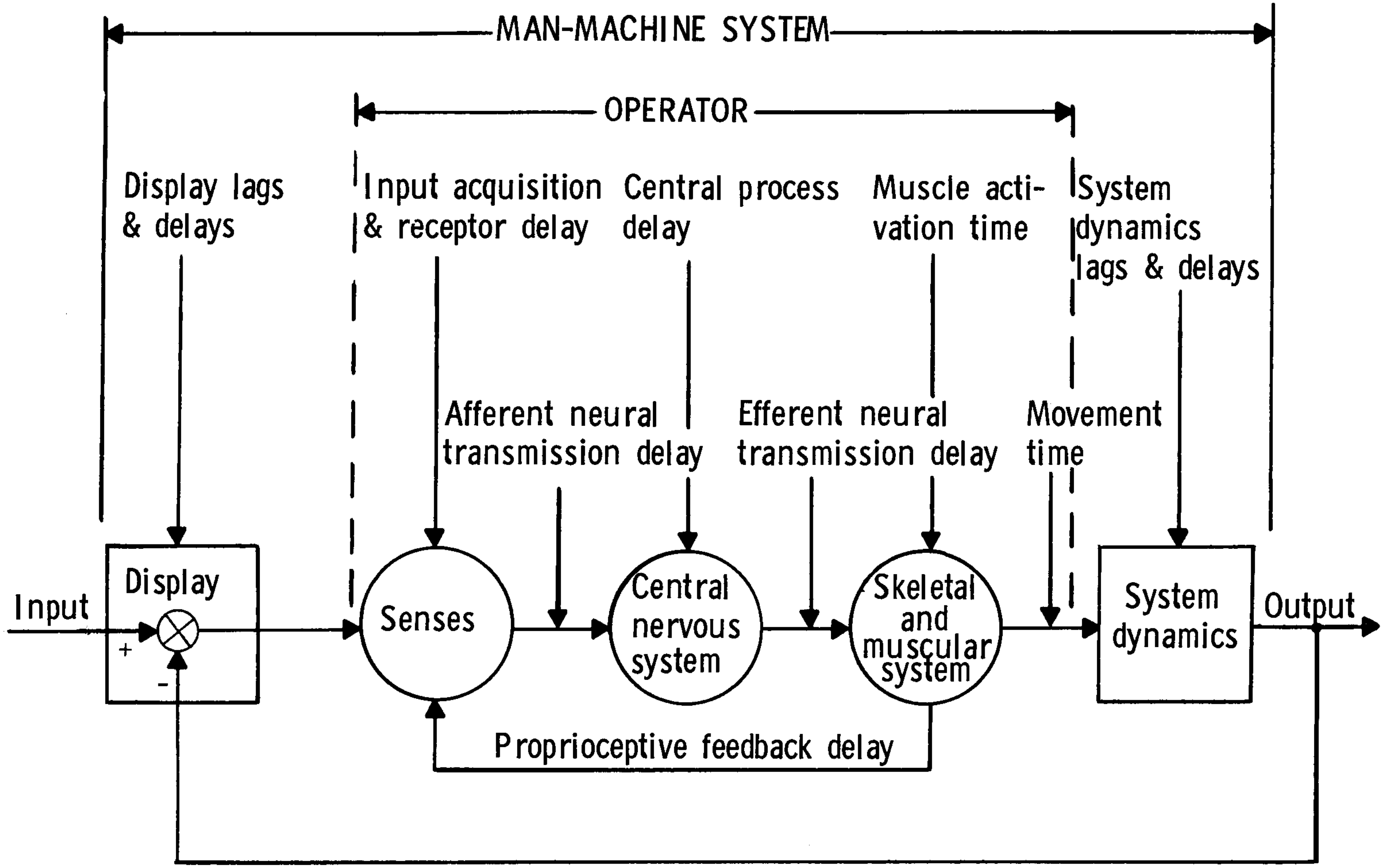

Figure 1. Schematic diagram of operator and system lags and delays in a manual control system.

McGrath, 1963), and stimulus factors will be discussed in following sections. Our present concern is with differences in the speed of receptor processes across sense modalities.

Assuming equally effective displays, considerable difference in detection speed can be attributed to the various sense modalities stimulated. Each of the organism's senses is subject to a receptor delay, the duration of which is a function of the transduction process occurring at the receptor level. Due to the relative slowness of the photochemical transduction that takes place at the retina, the eye for example, has a considerably longer receptor delay than the ear. Kemp, Coppée and Robinson (1937) report that the cat's auditory receptor latency is about 1-2 ms, where 15-38 ms may elapse between visual stimulation and detectable neural activity in the optic nerve of the cat, rabbit, or primate (Bartley, 1934; Marshall, Talbot & Ades, 1943). Thus it appears that at least in lower animals and primates, the transduction process of the eye is on the order of fifteen times slower than that of the ear. Similar receptor delay differences can be expected to occur between other senses.

Neural transmission delays. -- The transmission of the neural impulse whether afferent, from the receptor to the cortex, or efferent, from the cortex to the effectors, requires a finite interval of time. Neural transmission delays are a function of fiber composition, the diameter, total length and complexity of synaptic connections in the neural pathway. Mammalian neural transmission speed has been observed to range from .6 to 120m/sec (Patton 1961a).

The minimal latency of response at the visual cortex for stimulation of the optic nerve near the retina has been reported to be on the order of 1.6 - 5.0 ms (Bartley, 1934; Bartley & Bishop, 1940; Bishop & O'Leary, 1940; Chang & Kaada, 1950; Marshall, Talbot & Ades, 1943). Subtracting the 1-2 ms auditory receptor latency from the time required for an auditory stimulus to reach the cortex, the auditory nerve transmission delay is estimated at 6-8 ms (Kemp, Coppée & Robinson, 1937). On the basis of conduction velocity (Gasser, 1943; Weddell, 1945) and length of the neural pathway (Spector, 1956) cutaneous sensation neural transmission delays are estimated to range between 10 and 100 ms. These estimates point out that differences ranging from 5-90 ms can be expected in afferent transmission delay across various sense modalities.

Since efferent neural pathways are also composed of neural fibers throughout the velocity spectrum, considerable variability can be expected in neural transmission delays to various effectors. The conduction velocity of the larger motor fibers to the hands, arms, and feet in man range from

30-120 m/sec (Spector, 1956). On the basis of this range of conduction velocity and the lengths of the various neural pathways to the limbs, efferent transmission delays for the limbs are estimated to be on the order of 10-20 ms.

Central process delays. -- Central delays are those delays that can be attributed to the organism's perceptual and cognitive processes. Central perceptual delays are a function of the time required to complete detection, recognition, discrimination, and identification activities; central cognitive delays are the result of the thinking, planning, and decision making processes. Central delays, both perceptual and cognitive, are in general the longest and most variable of the operator delays. Subtracting the estimated duration for all the operator delays except central delays from the time required to make the simplest nonreflexive response, central process delays are estimated to range from 70-100 ms i.e., at least half of the total simple reaction time is required for central processing. However, when the complexity of central processing exceeds that required for the most simple reaction, the duration of the central delay can greatly exceed that estimate. When there are several inputs or several states of the same input and each of which has an associated correct response, as in the choice reaction time and manual control situations, central processing time increases to on the order of 90-300 ms (Woodworth & Schlosberg, 1965).

Muscle latency and activation time. -- The latent period between myoneural junction depolarization and the beginning of a muscle response in most mammals is on the order of 1 ms. However, activation time, the interval between the beginning of depolarization and the peak of muscle tension, requires on the order of 7-120 ms. In general, muscle contraction time varies with the muscle type, mass, and neural innervation ratio (Woodbury & Ruch, 1961).

In mammals muscle contraction time varies considerably; there are "fast" and "slow" muscles. The internal rectus of the eye, for example, is a "fast" muscle with a contraction time of about 7.5 ms, while deep extensor muscles acting on single joints are "slow" muscles (94-120 ms). In general, fast muscles are those required for rapid movement; slow muscles are concerned with posture (Woodbury & Ruch, 1961). Human contraction time for the hand has been reported by two sources. Vörckel (1922, as reported in Woodworth & Schlosberg, 1965) found that muscle currents could be detected 30-40 ms before a noticeable hand reaction, whereas Eppler (1965) reports that muscle action potentials precede a 6" hand movement by approximately 70 ms. The differences in these figures can probably be attributed to the recording techniques employed. At any rate, our best estimate of limb muscle contraction time would be on the order of 30-70 ms.

Summary of operator lags and delays. -- On the basis of the foregoing analysis, it appears that the operator's fastest hand reaction to an expected visual or auditory stimulus is on the order of 113-328 ms; however, if there is more than one stimulus or several states of the same stimulus, each of which is associated with a particular correct response, disjunctive reaction time can be expected to range from 133-528 ms. These estimates are based upon the previous discussion and can be summarized as follows:

	Delay in ms[1]	
Delay Basis	One-Choice	Disjunctive
Receptor delays	1-38	1-38
Afferent transmission delays	2-100	2-100
Central process delays	70-100	90-300
Efferent transmission delays	10-20	10-20
Muscle latency and activation time	30-70	30-70
Reaction Time or Total Delay ≈	113-328	133-528

The above estimates assume that the stimulus-subject interface is optimum, the subject is well practiced and is prewarned a few seconds prior to stimulus presentation. These estimates correspond to those figures usually cited in the literature for simple one-choice and two- to four-choice disjunctive reaction times (cf: Woodworth & Schlosberg, 1965).

Equipment Lags and Delays

Delays, whether originating in the operator or in the electromechanical components of the system degrade operator and consequently system performance. In addition to operator delays, lags and delays often occur in

[1] The references for these values appear in previous sections of this discussion under the corresponding headings.

the control element, in the display, or in both loops simultaneously. In closed loop manual control systems, control lags and delays are conventionally defined as those occurring in the forward loop, between the controller output and the system output; display lags and delays are defined as those occurring in the feedback loop, between the system output and its display to the operator (see Figure 1).

As would be expected, control and display lags and delays degrade tracking performance (cf: Muckler & Obermayer, 1964); the degradation tends to increase with increasing magnitudes of delay (Conklin, 1957 & 1959; Wargo, 1966 & 1967; Warrick, 1949), with forcing function frequency, and with higher control orders (Adams, 1961). Also, degradation appears to be greater for display as opposed to control lags (Garvey, Sweeney & Birmingham, 1958).

The deleterious effects of lags and the differential effects of control and display lags on system performance appear to be largely due to the different ways in which the machine components of the system process the operator's noisy nonlinear output relative to the system error (Garvey, et al., 1958). In contrast, the degrading effects of control and display delays on system performance must be entirely attributed to the operator's inability to maintain a given level of control when the temporal integrity of his control activities and/or feedback is distorted. The addition of transmission delays to the operator's inherent reaction time delay results in a disruption of the operator's innate timing.

REACTION TIME: A REVIEW

The preceding neuroanatomical analysis suggests that man's fastest one-choice reaction time should be on the order of 113-328 ms, and his fastest disjunctive reaction time on the order of 133-528 ms. Before reviewing the experimental work relating to the stimulus, sense modality, central, and response factors that tend to cause considerable variability in reaction time, a brief statement of the relation of reaction time to tracking performance is in order.

Loveless and Holding (1959) report significant rank order correlation for practiced subjects between pursuit tracking performance and both one-choice (r = .86) and two-choice (r = .71) reaction time. An extensive study by Parker and Fleishman (1960) also indicates intercorrelations between simple and disjunctive reaction time and performance on a large number of psychomotor performance tests (e.g., visual pursuit, rudder control). It should be pointed out, however, that the input frequencies on these tracking tests are considerably below the operator's response cut-off frequency. The negative correlation between reaction time and tracking performance at high input frequencies is established indirectly by the fact that as total system delay is increased, tracking performance concomitantly decreases (cf: Adams, 1961 and 1962; Leslie & Thompson, 1966); and more directly, Eppler (1965) reports that techniques that tend to reduce operator reaction time, tend also to increase his maximum response frequency. Thus as tracking input frequencies increase, the negative correlation between reaction time and tracking performance increases.

Now that the importance of man's reaction time in determining his maximum response frequency (bandwidth) has been established, a brief review of the experimental work relating to reaction time is indicated. First, some definitions. Simple or one-choice reaction time is defined as the interval between the initial occurrence of a stimulus and the first sign of the subject's response. In a choice or disjunctive reaction time situation there are several stimuli or several states of the same stimulus each of which has an associated correct response; the subject responds as quickly as possible with the correct response to the particular stimulus presented. Extensive reviews of the reaction time literature appear elsewhere (cf: Teichner, 1954; Woodworth & Schlosberg, 1965). The following brief review will attempt to bring up to date those topics relevant to the subject at hand.

Stimulus-Receptor Factors

Teichner (1954) has pointed out a basic assumption of many investigators: that the neuroanatomical differences between various receptor systems should result in different reaction times when their respective adequate stimuli are equated in intensity. Since measurement scales that permit objective equating of different stimulus energies are yet to be developed, Teichner warns that comparison of reaction times across various modalities of stimulation should be interpreted with caution. Keeping this warning in mind, one is still impressed with the consistencies that do appear in the literature relating to cross-modality reaction times. For example, reaction times to visual stimuli have generally been found to be significantly slower than similar responses to auditory stimuli (Canfield, Comrey & Wilson, 1949; Elliot & Louttit, 1948; Swink, 1966; for older studies see Woodworth & Schlosberg, 1965). Ranking of the senses in speed of reaction began as early as 1934 when Robinson (as reported in Teichner, 1954) summarized the results of early cross-modality reaction time comparisons in a table which indicated that auditory reaction times were shorter than tactual, which in turn were shorter than visual. More recent studies support Robinson's conclusion that auditory reaction times are faster than visual, however the ranking of tactual reaction time appears to be a function of the form of tactual stimulus employed and the manner in which the stimulus effects the sense organ (Loeb & Hawkes, 1961; Teichner, 1954). A very recent study by Swink (1966) pointed out that at least one form of tactual stimulation, electro-pulse, results in faster reaction times than either visual or auditory stimulation. The fast reaction times for electrical stimulation reported by Swink may be due to the fact that electrical stimulation can bypass the receptors and act directly on the nerves.

Several investigators have reported that simultaneous presentation of stimuli to two or more senses reduces reaction time. As early as 1912 Todd (as reported in Teichner, 1954) found that various combinations of light, sound and electric shock in every case resulted in faster reaction times than the individual stimuli. Todd also found that the response to light-sound combination was not only faster than light alone but also faster than the fastest individual stimulus reaction time, that to sound. Bliss, Townsend, Crane and Link (1965) support Todd's conclusion by their results which indicate that combined visual-tactual (air jet) stimulation results in markedly shorter reaction times than either stimulus alone. The most recent ranking of reaction times across stimulus modalities and in various stimulus combinations is that reported by Swink (1966). On the basis of extensive laboratory investigation he ranked reaction times from the slowest to the fastest as follows: light, sound, shock, light-sound, light-shock, light-sound-shock.

Related to the simultaneous cross-modality studies are those studies dealing with bisensory and monosensory intramodality stimulation. Since both visual and auditory phenomena usually show differences when stimulation is either monosensory or bisensory, studies that indicate reaction time differences under these stimulation conditions are expected. As reported in the reviews of Teichner (1954), and Woodworth and Schlosberg (1965), Bliss (1893) found faster reaction times for binaural as opposed to monaural auditory stimuli while faster reaction times to binocular as opposed to monocular visual stimuli have been reported by Poffenberger (1912) and Smith (1952).

Neurophysiologically, the number of receptor cells stimulated is a function of the area, locus, and intensity of the stimulus (Granit, 1955). On the basis of neurophysiological data, it is expected that spatial and temporal summation and a concomitant reduction in reaction time would result from an increase in area and/or intensity of stimulation. Previous reviews have reported that Froeberg (1907) in the visual case and Wright (1951) with thermal stimuli found that, up to a point, as the area of stimulation increases, reaction time decreases. Also, as expected, reaction time decreases as stimulus intensity increases up to some limit. This relation has been consistently shown for visual, auditory, gustatory, thermal, and pain stimuli. In the majority of cases cited, the relation between reaction time and stimulus intensity has been reported to be non-linear (Woodworth & Schlosberg, 1965).

Central Process Factors

It was previously estimated that man's central process delay for a simple reaction was on the order of 70-100 ms while in a choice reaction situation central delays range from 90-300 ms. Central process delays were dichotomized into perceptual and cognitive components: perceptual components were defined as those delays due to detection, identification and recognition of the stimulus while cognitive components as those due mainly to the decision and planning processes.

Kristofferson (1965a) recently investigated the perceptual components of central delay. Employing the perceptual discrimination experimental paradigm, Kristofferson found that: (a) there is a minimum time of approximately 60 ms which must separate two independent signals for them to be discriminated as successive signals 100% of the time, and (b) the average time required to switch from one sensory channel to another is also about 60 ms. Based upon these results, Kristofferson hypothesized that the switching of attention is controlled by a periodic mechanism that has a time cycle of about 60 ms. In a later publication, Kristofferson (1965b) presents experimental evidence indicating that this attention cycle time is approximately equal to the interval between zero-crossing of the cortex's alpha rhythms. On the basis of Kristofferson's work, we might attribute up to 60 ms of the operator's central delay to central perceptual factors. Any additional delay can be attributed to extended perceptual delays in addition to the cognitive central factors.

The major cognitive factor in reaction time is probably decision time. Studies relating to decision time usually incorporate the choice reaction time paradigm. In general, a minimum of 20-200 ms is added to the duration of the simple reaction time when the subject is given a choice response (Woodworth & Schlosberg, 1965). Research indicates that decision time increases with: (a) the number of stimulus alternatives (Bartz, 1962; Brebner & Gordon, 1962), (b) the number of possible responses (Bricker, 1955; Wiggins, 1957), (c) the similarity of the stimuli (Henmon, 1906 in Woodworth & Schlosberg, 1965), and (d) with sensory channel uncertainty (Kristofferson, 1965a).

A study by Bliss, Townsend, Crane and Link (1965) indicates that decision time may also be a function of the sense stimulated. These investigators compared visual and tactile (air jet) simple reaction time and found them about equal; however, when employing the same stimuli in a disjunctive reaction time situation, they reported large reaction time differences, with visual stimuli 40-50 ms faster than tactile. These results were interpreted as indicating that decision time for tactile is considerably longer than that for visual stimuli. The need for similar cross-modality comparisons using other sense combinations is indicated by these results.

As was stated previously and is suggested by the above, one of the longest operator delays is due to central processing time. Central delays are also considerably more variable than the other operator delays because of the many stimulus, response, and organismic factors that influence them. The shortest central delay in a simple reaction time situation is probably around 70-100 ms, up to 60 ms of which corresponds to central perceptual delays and the remainder of which corresponds to decision time. As the complexity of the stimulus, response, and decision process increases, central delay will correspondingly increase.

Response Members

Considerable investigation has been devoted to the study of speed of reaction of various response members. These investigations have implications not only for the problem of man's limited speed of response, but also for the related problem of his limited response flexibility.

Studies of reaction time across responding members suggest that there are significant differences between various effectors. These differences seem to be at least partly due to: (a) the closeness of the responding member to the motor cortex, and (b) the muscular force to inertia ratio of the effector. Seashore and Seashore (1941) observed the jaw, hand, and foot auditory reaction time of fifty male college students and found the jaw reaction time faster than that of the hand which in turn was faster than foot reaction time. More recently, Barlow (1964) reported that the disjunctive reaction time for occular movement was on the order of 170-240 ms, considerably faster than would be expected of the limbs in a similar disjunctive situation. Hathaway (1935) pointed out differences in reaction time due to the different force-mass ratio of the effectors. He found that arm movement reaction time was slower than that for finger movement. However, when the mass of the arm was bypassed by the use of muscle action potentials as an output member, Wargo, Kelley, Prosin and Mitchell (1967) found that the disjunctive reaction time of the arm was on the order of

100 ms faster than on comparable hand switch reaction time. These studies clearly indicate that there are significant differences in the reaction time of various response members. They also suggest that these differences are due to the closeness of the responding members to the cortex and the force-mass ratio of the effector.

Reaction Time and Response Frequency

Manual control frequency response is inherently limited by operator reaction time. The extent of performance degradation is, however, a function of the characteristics of the tracking situation and the input. In a tracking situation where the operator actually has a preview of the tracking course, as in many vehicle situations, the operator tends to respond one reaction time ahead of his response indicator -- a strategy easily adopted and usually successful. However, in pursuit and compensatory tracking where input preview is impossible, the operator is forced to predict the track one reaction time ahead and respond on the basis of his prediction. In general, the operator is quite accurate in his prediction when the input is simple and regular. When the tracking input is irregular however, operator prediction, even as short as a reaction time delay, tends to be inaccurate. Nevertheless, if the frequencies are not too high, with practice the operator can often predict better than chance. The operator adopts a compromise strategy which accepts some degree of error in prediction in order to reduce mean tracking error. As the frequency of the track increases however, reaction time delay results in greater performance degradation. With irregular inputs of high frequency (.7 - 1.5 cps) the operator's ability to predict one reaction time ahead is not far from the chance level. If he abandons prediction and attempts to track the input as he sees it, he will just as likely increase as decrease the system error. With random inputs, as the frequency of the forcing function increases, operator response tends to become increasingly out of phase with the input. When the forcing function frequency approaches one cycle/sec, operator response tends to be approximately 90° out of phase with the input, i.e. on the average, half of the time the operator will be correcting an input that is correcting itself, and the remaining time he will be increasing the size of the error caused by the input (Poulton, 1966).

Figure 2 illustrates the effect of delays on one-axis pursuit tracking of a relatively random input with a position control. This figure depicts the relation between system delay and cut-off frequency, i.e. the point at which tracking performance falls to 70.7% of a perfect tracking score. In this illustration, operator (τ_1) and system delays (τ_2) are transmission

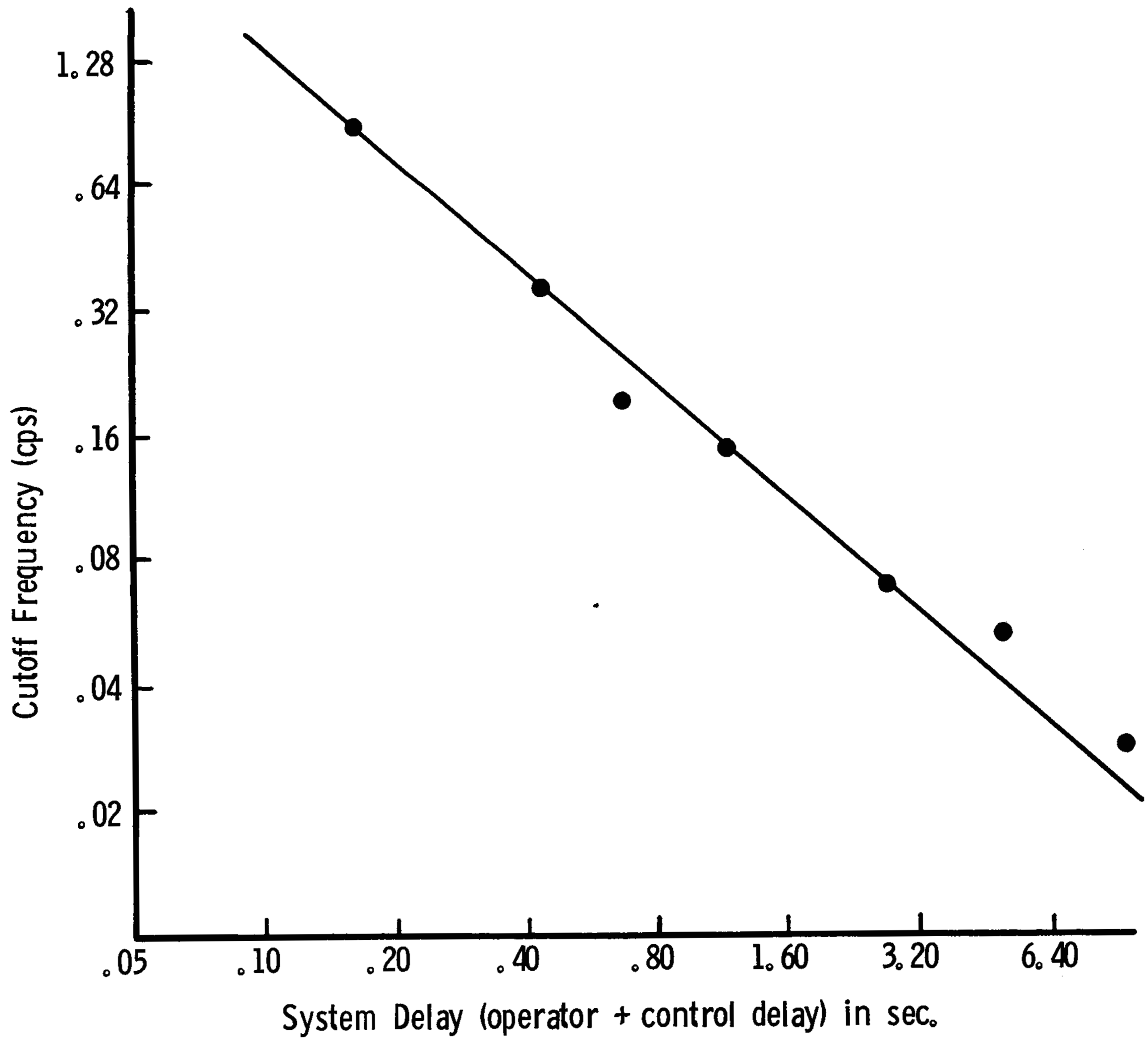

Figure 2. The effect of system delays on one-axis pursuit tracking performance. Adapted from data by Leslie and Thompson (1966).

delays[1] which when cascaded in the forward loop of a control system are additive. Therefore the values on the abcissa in Figure 2 can be considered the operator reaction time plus some value of control delay greater than zero. The best fit curve for these data takes the form of:

$$f_{co} = \frac{0.16}{(\tau_1 + \tau_2)\ 0.85} \quad \text{where,}$$

f_{co} = cut-off frequency

τ_1 = operator delay ($\tau > 0$)

τ_2 = control delay ($\tau_2 \geq 0$), and

$\tau_1 + \tau_2 \geq .10$

Cut-off frequency-system-delay curves such as Figure 2 change with alterations in system and input parameters. Nevertheless, Figure 2 illustrates the order of increase or decrease in system response frequency that can accrue from reduction or addition in system delays.

OPERATOR RESPONSE FLEXIBILITY

In addition to the limited control that man can extend over his effectors, his ability to simultaneously control several inputs is limited by the dearth of manual control research directed at taking advantage of responding members other than the hands, arms, and feet. Recently, however, considerable impetus in the direction of increasing man's response flexibility has resulted from research relating to prosthetic and orthotic device development. The primary focus of this research is on development techniques and devices that make use of weak muscles or functionally replace missing limbs. Research is directed at amplification of existing functions and at mimicking normal but missing control activities. Of the major developments resulting from this work, among the most important for increasing man's response flexibility are: (a) the development of muscle training techniques that improve voluntary control over the musculature, (b) the finding that man is a

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[1] Transfer function = $e^{-\tau s}$, where _e_ is the base of the natural logarithm system, τ is the delay in seconds, and _s_ is the Laplace operator.

source of innumerable useable control signals, muscle action potentials (MAP), and (c) the development of practical devices to make use of MAP for control activities.

Man has voluntary control to some extent over the majority of his skeletal muscles, including those not normally used in control activities, e.g., those of the face, neck, eyes, and ears. Training techniques have recently been developed that make possible precise voluntary control over the skeletal muscles other than those of the limbs (Bennett, 1958). The feasibility of these techniques in the development of voluntary control over more exotic muscles has recently been demonstrated by Bontrager (1965).

In addition to the possibility of using muscle groups other than those of the limbs for control effectors, Basmajian (1963) has recently reported that it is possible for man to learn to exert voluntary control over single units of muscular contraction of which there are tens of thousands in the human body. Thus, man has thousands of control effectors that conceivably can be used for manual control.

The fact that man can learn to control most of his skeletal musculature voluntarily does not mean that all of these effectors will be practical for manual control. However, with development of and advances in the detection and processing of muscle action potentials, manual control with many different skeletal muscle groups will become a reality. Currently, prosthetic and orthotic MAP controlled devices are in the prototype stage and intensive research is being carried out to improve MAP control.

TECHNIQUES FOR INCREASING MAN'S RESPONSE FREQUENCY AND FLEXIBILITY

Previous discussion defined the limitations on man's response speed, frequency, and flexibility; analyzed the neuroanatomical, psychological, and physical basis for these limitations; and implicitly suggested advanced manual control techniques for overcoming them. The remaining discussion will focus on a review of advanced control and display techniques that show promise in overcoming these limitations.

The most promising techniques for increasing man's response speed, frequency, and flexibility in the manual control context can be categorized as perceptual, cognitive and motor. In general, perceptual and cognitive techniques are those that are concerned with sensory stimulation, receptors, attention, detection, identification, planning, and decision making. Implementation of such techniques is dependent on display device development. The most promising perceptual-cognitive techniques for increasing man's response speed and frequency include:

1. Use of sense modalities with short receptor delays (on the basis of analysis a saving of approximately 30 ms; see Swink, 1966 for data verification),

2. Cross-modality input display (an additional saving of up to 20 ms; see Swink, 1966), and

3. Facilitation of operator input-output prediction (theoretically, if there is perfect prediction, the operator overcomes his reaction time delay; see Poulton, 1966).

In addition to the above perceptual and cognitive techniques, there are several techniques related to the use of responding members (motor techniques) which show promise in increasing man's speed and frequency of response:

1. Use of responding members closer to the cortex (a saving of up to 30 ms; see Seashore & Seashore, 1941),

2. Use of responding members with optimal force-inertia ratios (a saving of up to 90 ms; see Barlow, 1964) and

3. Direct use of muscle action potentials for control (a saving of up to 100 ms; see Wargo, et al., 1967).

On the basis of the above techniques it is estimated that a total potential reduction in reaction time on the order of 20-200 ms could accrue from advanced display and response device development. Theoretically, with facilitation of operator prediction, it is even conceivable that reaction time delay could be completely eliminated. It is uncertain whether all of these techniques and their potential savings can be realized. Nevertheless, on the basis of these estimates and Figure 2, it appears that these techniques could result in an appreciable increase in operator response frequency.

The most promising techniques for increasing man's response flexibility include:

1. Training the operator to use some of his more exotic potential output members,

2. Direct use of output members (other than the limbs) over which the operator has relatively precise voluntary control e.g., facial muscles, the eye, and

3. Use of operator muscle action potentials as a source of control signals.

The above suggestions require advanced manual control technique and device development for their implementation. The remainder of this discussion will focus on those display and control device techniques that should facilitate an increase in operator response frequency and flexibility.

Display Devices

One approach to increasing man's speed and consequently his frequency response is to develop display systems for those senses that have shorter receptor delays, e.g., the auditory and cutaneous senses. Currently there is considerable activity devoted to the development of auditory and tactual displays for various types of manual control systems. Most of this work is in the pioneering stages and none of it seems to be specifically directed to the development of display systems that will increase man's speed of response. Nevertheless, since reaction times to auditory and tactual stimuli are generally shorter than those to visual stimuli and since simultaneous stimulation of several senses results in shorter response latency, the research on tactual and auditory displays is relevant to the topic at hand.

Considerable exploratory work relating to the development of tactual displays has been reported (Bliss & Crane, 1965; Bliss, Townsend, Crane & Link, 1965; Durr, 1961; Geldard, 1961; Hirsh & Kadushin, 1964; Howell & Briggs, 1959; and Wissenberger & Sheridan, 1962); however, at present, a practical tactual display is yet to be developed. Geldard (1961) for example, developed a tactual display which consisted of a group of vibrators strapped across the operator's chest. Tracking error was displayed by the order of the vibrator activation, the larger the error the more frequently the vibrations occurred. Comparing this vibratory display to a corresponding visual display of three lights, Geldard reports that tracking performance with the vibratory display was comparable to performance with the visual display. However, since the visual display in this study was quite rudimentary, it is expected that considerable difference in favor of the visual display would accrue if a more conventional visual display were employed in the comparison. Probably the most extensive work relating to tactual display was recently reported by Seeley & Bliss (1966). They developed an air jet tactual display and compared compensatory tracking with the air jet display to tracking with a quantized and with a continuous visual display. The tactual display consisted of a 7x7 array of air jet stimulators, with the center jet acting as the on-target reference. The array of air jets was attached to the subject's face with the center element placed over the tip of the nose and the most extreme elements located at the lower forehead, the upper lip, and the medial portion of the cheeks. The two visual displays consisted of an oscilloscope and a 7x7 array of neon lights corresponding in layout to the tactual display. The subjects were required to track a complex course in two axes with a position control. The results indicated that under several combinations of display gain and command signal bandwidth, performance with the tactual and discrete visual display was approximately equal, however, both of these displays were inferior to the continuous visual display in terms of mean-squared error.

Seeley & Bliss' results and those of the other researchers referenced above, indicate that considerable work is necessary to develop a tactual display that approaches the effectiveness of a continuous visual display. However, when performance need not be as accurate as that obtained with a continuous visual display, or when freeing the distance receptors for another activity is an advantage, the tactual display is an attractive alternative. Also, the faster response times possible with certain tactual displays (at least electro-pulse; see Swink, 1966), make tactual display an attractive possibility for increasing man's response frequency.

As with tactual display research, auditory display development has been exploratory in nature with apparently none of it directed to increasing operator response bandwidth. Nevertheless, auditory displays do hold promise for increasing operator response frequency.

The human operator is capable of making absolute judgments of frequency, intensity, and complexity of auditory stimuli; however, the human ear, as the other senses, is more sensitive to relative difference between stimulus parameters. Therefore, most practical auditory displays developed to date have encoded various input dimensions in terms of monaural, diotic or dichotic, intensity, frequency, or pulse rate difference. In general, when one dimension auditory tracking has been compared to visual tracking, visual tracking has been found superior (Goldman, 1959; Harris, Pikler & Murphy, 1963; Humphrey & Thompson, 1952a, 1952b, 1953; Pikler & Harris, 1960; Taylor, 1963; Wargo, 1967). However, the information transmission capabilities of sensory channels increase, up to a point, with the dimensionality of the stimulus. Therefore, as Pollack and Fick (1954) have pointed out, multidimensional auditory encoding can increase the information transmission capability of auditory stimuli and thereby improve auditory tracking.

Following up deFlorez's (1936) early demonstration of the feasibility of multidimensional auditory tracking, Forbes, Garner, and Howard (1945) developed an auditory display that proved effective for flight by auditory reference (FLYBAR). After a series of preliminary studies, they selected the most practical signal combination of those tested and compared visual and auditory "flying" in a Link Trainer. Bank was displayed by binaurally varying frequency and intensity of a single tone. Intensity differences between the ears indicated the side of bank and frequency change, the degree of bank. Airspeed was displayed by the difference between a standard "beep" and an indicator "beep." This multidimensional signal combination proved to be as effective as the conventional visual displays for "flying" a Link Trainer. Hodgson (1966) in a more recent multidimensional auditory display study, developed a two-axis tracking system which displayed vertical axis error by pitch difference between a fixed reference and a varying frequency tone, and horizontal axis error by a pulsing ("putt-putt" sounding) signal to either ear, the pulse rate of which corresponded to the degree of error. Two-axis position control tracking performance with a conventional CRT display proved to be significantly superior to auditory tracking performance. However, when the operator was required to perform a secondary visual search task in addition to tracking, auditory tracking performance was in most cases as accurate as visual tracking.

It appears that tracking with either an auditory or tactual display is practical when performance need not be as accurate as comparable visual tracking performance. The primary advantages of such displays is in unburdening the visual receptors of the operator. When a trade-off of accuracy for unburdening of the visual sense is acceptable, both auditory and tactual displays are attractive alternatives. Unfortunately most auditory and tactual tracking evaluations have employed forcing function frequencies considerably below the operator's critical cut-off frequency. Consequently, direct evidence in support of the expectation that these displays increase operator response bandwidth is unavailable.

Cross-modality display of tracking inputs would, on the basis of reaction time studies, be expected to increase operator response bandwidth. However, as with single modality tactual and auditory display evaluations, simultaneous display tracking studies have not been directly concerned with operator response frequency. Nevertheless, at frequencies below operator cut-off, simultaneous visual-tactual and visual-auditory displays have been demonstrated to improve tracking performance. Hirsh and Kadushin (1964) report a cross-modality visual-tactual display study. On the thumb and index finger of the hand used to manipulate the control of a one-dimensional complex dynamic tracking system, vibrators were attached to display rate of error change. The track consisted of step inputs and was displayed via a compensatory visual display. Comparison of visual to visual-vibratory tracking performance indicated that the combined display was superior to the visual display. The error rate of change displayed by the vibrators seemed to call attention to changes in error and thereby reduce the possibility of vigilance lapses. Hodgson (1966) in his auditory display evaluation partly described above, compared simultaneous visual-auditory tracking performance to visual tracking performance. The cross-modality display was a simple combination of his auditory and visual display described earlier. Hodgson found that combined display tracking was superior to tracking with either display alone. The combined display was also superior to the visual display when first-order control lags were imposed in the tracking system and when a secondary visual search task was performed simultaneously with the tracking task.

The preceding studies point out the improvement in tracking performance that can accrue from simultaneous cross-modality display of the track. It is also expected, on the basis of the cross-modality reaction time studies, that cross-modality display in a tracking situation could increase operator response bandwidth. However, this expectation is yet to be verified.

In addition to the display devices described above, displays that facilitate operator prediction of input, output, or combination thereof, can increase operator bandwidth. When the future state of the input is directly viewed or displayed to the operator, his reaction time to input changes is not a major limitation on his response frequency. However, when preview is not possible, as in compensatory and pursuit tracking, the operator cannot anticipate his response one reaction time ahead and consequently his response delay degrades his performance. In such situations anticipation can be facilitated, and degradation in performance resulting from operator reaction time can be minimized, through the use of display devices that permit preview or in some ways predict the future of the input. In a system with complex dynamics, the operator's principal limitation on his response frequency may be his inability to predict the outcome of his control activities. When prediction of output is a limitation on operator performance, a predictive display of output is in order. Kelley (1958, 1960a, 1960b, 1962) describes such a display. The predictor instrument, as developed by Kelley, is based upon a fast-time model of the control system which displays to the operator the effect of his various control activities on the future system output. The predictor display has been reported to substantially improve operator control of systems with complex dynamics (Besco, 1964; Fargel & Ulbrich, 1963; Kelley, 1958, 1960a, 1960b, 1962; McCoy & Frost, 1964; Bernotat & Widlock, 1966).

Response Devices

Many of the response devices that show promise in increasing man's speed and response frequency also tend to free the operator's limbs and thereby increase his response flexibility. The primary impetus leading to the development of many of these devices has, in fact, derived from the desire to unburden the operator's limbs.

By definition, reaction time estimates do not include any significant movement time. In the manual control context, however, movement time is a significant component of total response time. The operator's response to a step input typically consists of a reaction time, a primary or gross movement time, and a secondary or fine adjustment time. Primary movement tends to reduce error to within 10% (Vince, 1948) and the secondary movement tends to be accurate within 10% of its own value reducing error to on the order of 1% of its original value (Craik, 1947). The duration of primary and secondary movement time tends to vary with the extent of movement, input, and control dynamics.

An estimate of minimum movement time can be derived from data reported by Brown and Slater-Hammel (1948). They report that a one-inch misalignment of a very light pointer can be corrected in about 550 ms, 250 ms of which corresponds to reaction time, 200 ms to primary movement, and about 100 ms to secondary movement time. On the basis of these data, a minimum movement time on the order of 300 ms can be expected for most control activities. This estimate when added to the 40-90 ms estimated earlier for efferent transmission and muscle activation time, indicates that 346-396 ms delay can be expected between the decision to activate a control and completion of the control activity. That is, more than half of the total response time is due to activation and movement time.

Since a considerable portion of total response time consists of movement time, it is expected that any control device that substantially reduces movement time will tend to increase the operator's response frequency. One such device is an isometric control (also known as a stiff stick, force, or pressure control). An isometric control is activated by the force exerted on the control rather than control displacement. Therefore it considerably reduces the movement time usually required by the conventional displacement control. At moderate input frequencies, tracking performance with isometric controls has been reported to be 10-50% superior to performance with comparable displacement controls (Burke & Gibbs, 1965; Gibbs, 1954; North and Limnicki, 1961). In these studies, isometric control superiority increased with increasing task difficulty. At high input frequencies, Eppler (1965) and McRuer & Magdaleno (1966) report that a substantial increase in operator response frequency is afforded with an isometric control. It appears that isometric control is superior to displacement control and that the superiority increases as the frequency of the input increases. However, isometric controls are usually hand or foot operated so they do not in themselves increase the operator's flexibility of response in terms of freeing his limbs. Nevertheless, it is within state-of-the-art to develop isometric controls that are, for example, jaw operated, and thereby increase both man's response frequency and flexibility.

Another approach to increasing man's response frequency and flexibility is to employ the eye as a control effector. To track with the eye, the operator simply changes his direction of gaze to correspond with the target. In the manual control context, when tracking random signals, the eye's reaction time has been reported to range between 150 and 200 ms (Barlow, 1964; Stark, Vossius & Young, 1962). These reaction time figures are at the short end of the range which is generally found in a disjunctive situation when the subject expects the signal (200 - 500 ms; see Woodworth & Schlosberg, 1965). In addition to having a relatively quick reaction time, the muscles that control eye movement are among the fastest contracting muscles, consequently contraction and movement time are extremely rapid (Woodbury & Ruch, 1961). Therefore, it is expected that a considerable increase in man's response speed and frequency could accrue from use of the eye as a response member. Use of the eye as a response member has an additional advantage of freeing man's hands, feet, and limbs for other control activities.

To use the eye as a response member, some method of movement detection must be employed. Currently there are at least three methods to detect eye movement: measurement of corneoretinal potentials via surface electrodes around the eye's orbit, measurement of light reflection differential between the sclera and iris, and tracking the reflection of a special light focussed obliquely on the cornea. Reflection techniques can be used to detect both horizontal and vertical movements, however, the corneoretinal potential technique is limited to detection of horizontal movements because upward rotation of the eye during eye blinks distorts vertical movement detection. All three methods measure eye movements relative to the head and consequently require that the device be mounted on a helmet or that the head be kept stationary via a device such as a bite board.

Early eye tracking investigations demonstrated the feasibility of eye tracking and suggested its further development for situations where hand tracking accuracy is not required or when freeing the limbs for other control activities is an advantage (Ford & White, 1959; Lockhard & Fozard, 1956; Sampson, Coleman & Elkin, 1959). Eppler (1965) in comparing his response frequency curves for isometric and MAP control to the eye tracking results of Young (1962), Stark, Vossius and Young (1962), found that eye tracking was comparable in speed of response to that of isometric and MAP control. On the basis of this exploratory work, it appears that the eye shows considerable promise in increasing operator response speed, frequency, and flexibility.

Probably the most significant development for increasing man's response speed, frequency, and flexibility has been the recent improvements in MAP detection and control activation. The major advantages of MAP control for increasing operator speed and frequency of response are: (a) the reduction of contraction and movement time that accrues from bypassing the muscle lags, and (b) the possibility of the operator effecting control by simply thinking of the control activity. In terms of increasing operator response flexibility, MAP control is advantageous because: (a) it can be derived from most skeletal musculature, and (b) it is relatively unaffected by varying "g" loadings.

MAP control devices are still in their initial stages of development, however research that has been reported is quite encouraging. Relating to operator speed of response, Vodovnik and Ing (1964) report the development of an automobile braking system that uses MAP as the actuating signal. Though still in its preliminary stage of development the device has proven to reduce operator braking time; however, the reduction in braking time of 350 ms expected by the authors has not yet been obtained. Wargo, et al. (1967) report a study in which visual, auditory, and combined visual-auditory MAP and hand switch disjunctive reaction times of three subjects were compared. The display effects were small but significant; however, across displays, MAP control resulted in a reduction in reaction time on the order of 100 ms. In relation to operator response frequency, Eppler (1965) compared the tracking of step and continuous random inputs when the control device was a displacement, an isometric and a MAP control. His results indicate that the operator's bandwidth or frequency response increases with both isometric and MAP control as compared to the usual displacement control. MAP control resulted in the greatest increase in operator bandwidth, however, the random noise component of the operator's response increased at about the same order as did his frequency response.

In addition to the increased speed and response frequency that seems possible with MAP control, considerable flexibility of response is possible through the use of MAP signals originating from sources other than the limbs. However, most prosthetic and orthotic device work to date (see Bottomley, Wilson & Nightingale, 1963; Dodge, 1966) and even the human amplifying exoskeleton research (Wasserman, 1964) has tended to focus on deriving MAP signals from the hands, feet, and limbs. Nevertheless, as pointed out earlier, it is feasible to use MAP control signals from head, face, and other muscle groups to permit freedom of the limbs.

Practical MAP manual control systems are by no means a reality at present. Some insight into the problems facing the MAP control designer are detailed in a report by Lyman, Weltman and Groth (1966). However, advanced manual control technique development in conjunction with development of better MAP control signal detection and processing will eventually make MAP control devices a practical reality.

CONCLUDING REMARKS

On the assumption that the primary reason for placing a human operator in a system's control loop is to utilize his unique perceptual and cognitive adaptability, the literature relating to response limitations on these skills was reviewed and analyzed. Review and analysis indicated that considerable improvement in operator response speed, frequency and flexibility could accrue from development of advanced control and display devices. With the demands being placed on the human operator by modern complex high-speed control systems, it is expected that many of the suggested devices will become a practical reality in the near future.

SECTION II

MUSCLE ACTION POTENTIAL AND HAND SWITCH DISJUNCTIVE REACTION TIME TO VISUAL, AUDITORY, AND COMBINED VISUAL-AUDITORY DISPLAYS

MUSCLE ACTION POTENTIAL AND HAND SWITCH DISJUNCTIVE REACTION TIME TO VISUAL, AUDITORY, AND COMBINED VISUAL-AUDITORY DISPLAYS[1]

The previous review and analysis of human operator response limitations suggested several techniques for increasing man's speed and flexibility of response. Many of the techniques suggested require considerable development before they become practical for incorporation into manual control systems, while others appear to be immediately practical. Among the most promising techniques for immediate application are:

- auditory display
- simultaneous cross-modality display, and
- muscle action potential (MAP) control.

A control-display device incorporating the above techniques should substantially increase operator response speed, frequency, and flexibility. However, prior to the development of such a device, it was decided to further evaluate these techniques in a situation more analogous to manual control than the simple reaction time situation. A disjunctive (choice) reaction time situation configured such that it resembled a one-axis compensatory tracking task was selected as the vehicle for evaluation.

There were several reasons for the decision to empirically evaluate the above techniques in a choice reaction time situation. Primary among these was the fact that most of the evidence recommending auditory and simultaneous cross-modality displays derives from simple reaction time studies from which generalization to manual control is tenuous. For example, Bliss, et al. (1965) found that visual and tactual (air jet) simple reaction times were essentially equal, but tactual disjunctive reaction times were found to be considerably slower than visual. Since manual control tasks are more nearly analogous to choice reaction time situations and

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[1] This study was reported at the 1967 Eastern Psychological Association Meeting in Boston, April 1967 and will soon appear in the IEEE Transactions on Human Factors in Electronics.

since generalization from simple reaction time results to manual control appears unwarranted, evaluation of the above techniques using disjunctive reaction time was indicated. In addition to the desire to verify the advantages of auditory and cross-modality display in the choice reaction time situation, there was a desire to determine the saving in reaction time that accrues from using MAP control. At present little data are available in relation to MAP reaction times and none is available in relation to choice MAP reaction times. A final though equally important reason for this study was the desire to evaluate these techniques prior to any large investment in time and money for control-display device development.

Evaluation consisted of a comparison of MAP and hand switch disjunctive reaction times to visual, auditory, and combined visual-auditory display. It was expected that MAP responses would be considerably faster than hand switch responses. It was also predicted that within each response mode the auditory display would result in faster choice reaction times than the visual display and that simultaneous display would be faster than either of the individual displays.

METHOD

Apparatus

The equipment consisted of a control-display console, stimulus programming digital and analog equipment, and an elapsed time electronic counter. The control-display console generated three displays -- visual, auditory, and a combined visual-auditory. The control was either a spring centered toggle microswitch or the amplified muscle action potentials from the S's right forearm. The visual display was presented on a 17" cathode ray oscilloscope (CRO), the auditory via a head set, the visual-auditory by both the CRO and head set.

The visual display consisted of a 2" horizontal line centered on the face of the CRO. The line was programmed to deflect approximately 3" above or below the centered position. The S's task was to return the line to center position as quickly as possible via a compensatory control movement. The interdeflection interval which ranged from three to five seconds, and the direction of deflection, were pseudo-randomly programmed by analog equipment. The auditory display consisted of a binaurally presented 880 cps tone which corresponded to the centered line on the visual display. The tone was programmed to jump to 1760 or to 440 cps via the same program employed with the visual display. The three tones were considerably above the absolute threshold of the Ss. As with the visual display, the S's task was to return the deflected tone to 880 cps as quickly as possible by a compensatory control movement. The visual-auditory display consisted of both display modes functioning simultaneously.

The spring-centered toggle microswitch was positioned at arm level and below the center of the display. The control-display configuration was such that when the horizontal line or tone was deflected up, the proper control action was a downward response of the toggle switch and vice versa. A small force (3.5 oz) and a slight deflection (.125 in) of the switch was sufficient to return the display to its center position or frequency.

The alternative response mode consisted of muscle action potentials picked up from the S's right forearm. These action potentials were preamplified by a BIOCOM Model 121 differential amplifier, filtered and further amplified by the analog equipment. The two pairs of active electrodes were positioned at the proximal portion of the forearm, one pair over the short radial-extensor muscles of the wrist located on the posterior (outer) side of the forearm and the other pair on the anterior (inward) side of the forearm over the radial-flexor muscles of the wrist. The active electrodes were spaced about 3.5 in apart along the length of the respective muscle groups with the common or ground electrode placed between them. The movement corresponding to the flexor and extensor action potentials was a flick of the wrist toward the anterior portion of the forearm, or in opposition, toward the posterior portion of the forearm. Signal amplification and sensitivity was adjusted such that with the hand in a semirelaxed position in line with the forearm, no response triggering occurred. Triggering was possible only by a rapid flick of the wrist.

A Hewlett Packard Model 522B elapsed time counter recorded the interval of time in milliseconds between the stimulus change and the onset of the correct response. Disjunctive reaction times were cumulatively displayed and the mean of every ten responses was recorded by the experimenter.

Procedure

Three males, two of which were college students and the third a college graduate, were employed as Ss. Their age range was 19-27 and they had no apparent visual or hearing defects.

Pretraining and data collection took place in a relatively quiet experimental laboratory. Ss were pretrained with the combined visual-auditory display in conjunction with each response mode. Pretraining consisted of approximately 250-300 responses elicited in groups of 50, with short rest periods interspersed between groups. Pretraining was discontinued when performance reached a plateau which was arbitrarily defined as some stabilized mean response time ± 30 ms for at least 50 trials.

After pretraining, 100 disjunctive reaction times were collected from each S at each display-response combination. This procedure was then replicated, resulting in a total of 200 data points per S at each display-response combination. Pretraining was repeated prior to the replication of the basic design.

Prior to data collection at any display-response combination, Ss were given 50 warm-up trials and a 5 min rest. Data were collected in two sessions each of which consisted of data collection across display types with the response mode fixed. The order of display-response combinations was systematically varied between replications to counterbalance fatigue and practice effects. Within each display-response combination two sets of 50 responses were elicited with a short rest period between sets. Rest periods were also interspersed between combinations and a minimum of four hours elapsed between sessions. From one to three days elapsed between initial data collection and the replication.

RESULTS

Figure 3 graphically illustrates the group mean reaction times based upon 200 responses per S for each display-response combination. This figure suggests that: (a) MAP responses were consistently and significantly faster than the hand switch responses across display modalities, and (b) the display effects were mixed within the switch response mode, however, within the MAP mode of response the combination display was faster than the auditory display and it, in turn, was faster than the visual display. Table I presents these data in terms of: (a) the mean response time in ms ($\bar{X}$) for each S at each display-response combination, (b) the standard error of the means ($SE_{\bar{X}}$), and (c) the mean across replication and Ss (M) for each response mode-display combination. Comparison of the individual S means ($\bar{X}$) across display-response combinations in Table I indicates that: (a) the display effects were more consistent within the MAP response mode, and (b) J.H.'s atypical auditory display performance within the hand switch response mode disproportionally inflated the group mean at that display-response combination. Perusal of the variability measures for each S across conditions clearly indicates that there was greater within and between subject variability across displays for the hand switch as compared to the MAP response.

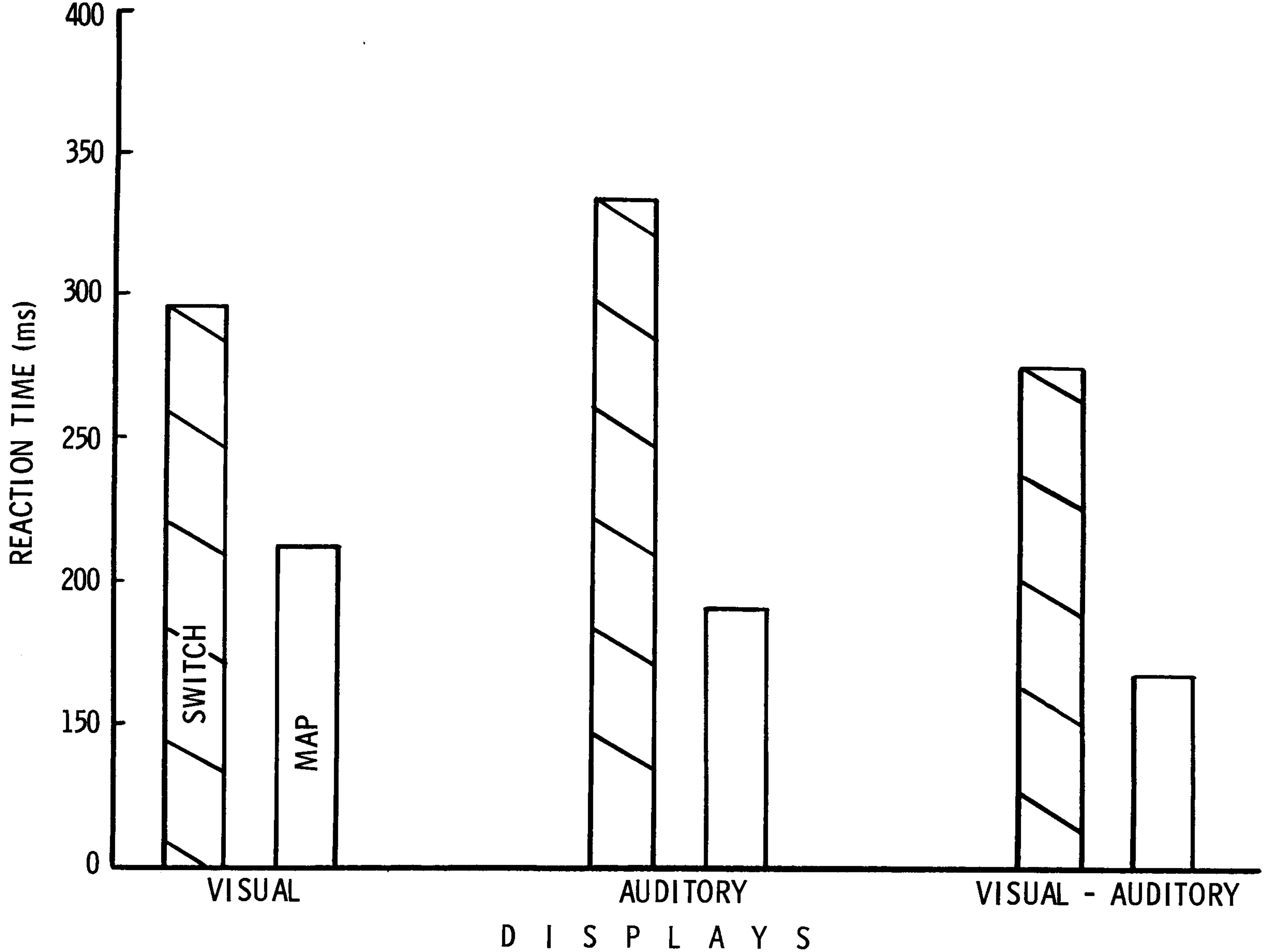

Figure 3. Mean disjunctive reaction time in milliseconds across display-response combinations.

TABLE I

MEAN REACTION TIMES FOR EACH S ($\overline{X}$), THE STANDARD ERROR OF THE MEANS ($SE_{\overline{X}}$) AND THE GROUP MEANS (M) ACROSS DISPLAY-RESPONSE COMBINATIONS

		Hand Switch Response					
		Visual		Auditory		Visual-Auditory	
Session	Subject	$\overline{X}$*	$SE_{\overline{X}}$	$\overline{X}$	$SE_{\overline{X}}$	$\overline{X}$	$SE_{\overline{X}}$
1	MW	262.19	22.25	295.34	11.20	234.39	9.94
	DW	302.24	9.55	286.92	12.99	274.26	13.15
	JH	323.29	14.19	434.01	16.15	335.92	9.62
2	MW	272.70	9.23	305.50	6.28	252.40	4.66
	DW	306.40	6.56	316.40	6.73	276.80	8.33
	JH	309.80	8.71	366.20	8.73	287.10	10.11
	M	296.03		334.06		276.83	

		MAP Response					
		Visual		Auditory		Visual-Auditory	
Session	Subject	$\overline{X}$*	$SE_{\overline{X}}$	$\overline{X}$	$SE_{\overline{X}}$	$\overline{X}$	$SE_{\overline{X}}$
1	MW	185.11	5.35	164.89	5.62	163.49	6.86
	DW	237.21	12.46	209.19	7.04	191.46	4.81
	JH	210.00	4.96	207.93	12.14	179.09	8.03
2	MW	191.70	7.38	165.00	3.83	150.00	3.18
	DW	228.20	12.75	189.10	6.18	168.00	7.42
	JH	213.40	11.48	201.20	7.98	162.10	3.37
	M	210.93		189.57		169.03	

*Based upon the mean of 10 means of 10 observations each.

Table II summarizes the 2X3X3 (20 observations/cell) variance analysis performed on these data. As suggested by Table II, the variance analysis indicated that the subject factor interacted with the display and response mode factors and with their interaction. Disregarding the subject interaction with display-response combinations, the interaction of display X response mode reached statistical significance, i.e., the effect of displays differed across response modes. As Table I indicates, J.H.'s atypical performance within the switch response mode disproportionately contributed to that interaction. The display effects were relatively consistent for the other two Ss within the switch response mode. Within the MAP response mode, the display effects were similar for all Ss.

Simple effect analysis, which is also summarized in Table II, indicates that the display effects at each response mode, and the response effects at each display type, were statistically significant. Comparison of the means via the Newman-Keules procedure indicated that all of the response mode differences across displays reached statistical significance ($p < .01$). All the display differences within the switch response also reached significance at the .01 level, however within the MAP response mode only the difference between the visual and combined display reached the .01 level of significance while the remaining differences were significant at the .05 level.

DISCUSSION

The results of this study indicate that: (a) MAP disjunctive reaction times are consistently and significantly faster than hand switch reaction times across visual, auditory and visual-auditory displays, and (b) combined visual-auditory display responses are considerably faster than visual responses.

The observed reduction in disjunctive reaction time accruing from use of MAP response was substantial considering the small force (3.5 oz) and extent of movement (.125 in) required for the comparison hand response. It appears that a considerable portion of this saving is primarily due to the reduction in muscle activation time usually required for a hand response. This point has a significant implication for control system design. The advantage of using MAP response as a means of reducing operator delay will tend to increase as the magnitude of the muscle activation and movement time that is bypassed increases.

In addition to reduction in reaction time, another advantage of MAP control is apparent. Since MAP responses can be detected from most muscle groups, it is conceivable that muscle groups other than those of

TABLE II
VARIANCE ANALYSIS (A) AND SIMPLE EFFECT ANALYSIS (B)

(A) Variance Analysis of Reaction Times

Source of Variation	df	MS	"F"
Subjects (A)	2	71,884.1	
Displays (B)	2	50,759.2	5.94[1]
Response Mode (C)	1	1,141,403.7	41.24*
AB	4	8,540.0	14.01**
AC	2	27,674.8	45.40**
BC	2	27,320.4	9.15*
ABC	4	2,986.3	4.90**
Within Cell	342	609.6	
Total	359		

(B) Simple Effects Analysis

Source of Variation	df	MS	"F"
Displays for Switch Response	2	51,726.95	17.32*
Displays for MAP Response	2	26,352.8	8.82*
Error (ABC)	4	2,986.3	
Response Mode for Visual	1	217,583.8	72.86**
Response Mode for Aud.	1	630,126.6	211.00**
Response Mode for Visual-Auditory	1	348,334.2	116.64**
Error (ABC)	4	2,986.3	

[1] $p < .10$ * $p < .05$ ** $p < .01$

the limbs can be employed as control effectors. Use of MAP responses from muscle groups other than the limbs should considerably increase man's manual control flexibility.

The display effects expected on the basis of previous work were evident within the MAP response mode but were not evident for the hand switch response. In both response modes, reaction times with the combined display were faster than with the visual display; however, responses to the auditory display in the hand response mode were not, as expected, faster than responses to the visual display. A possible explanation of this discrepancy can be found in the experimental procedure. Recall that during pretraining only combined display was employed. It seems possible that as a result of this pretraining procedure Ss were handicapped when responding to auditory signals. Post-experimental subjective reports from the Ss did suggest that during pretraining Ss used the auditory signal primarily as a cue to respond and that the direction of response cue was derived from the visual signal. On the basis of these reports, it appears that the pretraining procedure could have resulted in more control reversals when the Ss were responding to the auditory display. If this were the case, the handicap would tend to have a more extreme effect on the hand switch response, as observed, because of the movement-time required to make and then correct a wrong response. The greater reaction time observed for the auditory display within the hand switch response, therefore, appears to be an artifact of the experimental procedure. With proper pretraining, it is expected that performance with the toggle switch across displays would follow the expected trend -- that observed with the MAP response.

This study demonstrates that a substantial reduction in operator disjunctive response time accrues from the use of advanced manual control techniques such as: (a) the display of input to senses with relatively short receptor delays, (b) increasing the attention value of the input by simultaneous display to two-sense modalities, and (c) reducing muscle activation time and bypassing movement time via the use of muscle action potentials for control.

SECTION III

AN ULTRA-QUICK CONTROL-DISPLAY DEVICE

DESCRIPTION OF THE ULTRA-QUICK CONTROL-DISPLAY DEVICE

The results of the disjunctive reaction time study indicated that response speed with visual-auditory display and muscle action potential (MAP) control was approximately 125 ms faster than the conventional visual display hand control configuration. On the basis of this finding and human operator cut-off frequency curves such as Figure 2 (Section I, p. 16) it was expected that in many manual control situations a considerable increase in operator response bandwidth would accrue from use of a MAP control, visual-auditory display device. An additional advantage of such a control-display device would be the increased response flexibility offered the operator via MAP pick-up from muscle groups other than those of the limbs. It was therefore decided to develop a MAP control, visual-auditory display device that could be incorporated in a one or two axis acceleration tracking system.

The completed device can best be described as a self-contained two axis MAP control system, operable in three display modes (visual, auditory, and visual-auditory) and in two MAP output modes. The two output modes consist of: (1) a discrete three-state (+ 10v, 0v, - 10v at 2.2 ma) bang-bang mode, and (2) an integrated output mode which provides continuous constant-rate control signals. The choice of input-output modes is left to the operator; however, regardless of the display mode the output is always processed MAP signals. It should be emphasized that the device is only a control-display system, i.e., some external controlled element, such as a real or simulated spacecraft, tracking system, etc., is controlled via the device. Input signals from the external controlled element in the form of DC voltages are required to operate the displays, and output signals (in the form of DC voltages also) are supplied by the device.

The entire device weighs approximately 60 lbs and is contained in a 21" x 13" x 9.5" Halburton Model 165X-E1 aluminum carrying case. Figure 4, a sketch of the device, illustrates how the lower shell of the cabinet is functionally divided into three compartments: (1) visual displays -- scope, meters, and indicator lamps, (2) auditory display, and (3) MAP signal processing. Spare parts and earphone storage space is provided in the upper shell of the carrying case. The external power requirement for the device is 110v AC power for the cathode ray oscilloscope (CRO) and battery charger. The required input signals are DC voltages in the range ± 100v in each axis, representing the variable(s) to be controlled. The remaining power needs for the system are met with rechargeable nickel-cadmium batteries, located in the lower shell of the case. The device is capable of operation on batteries if the meter visual display is used rather than the CRO.

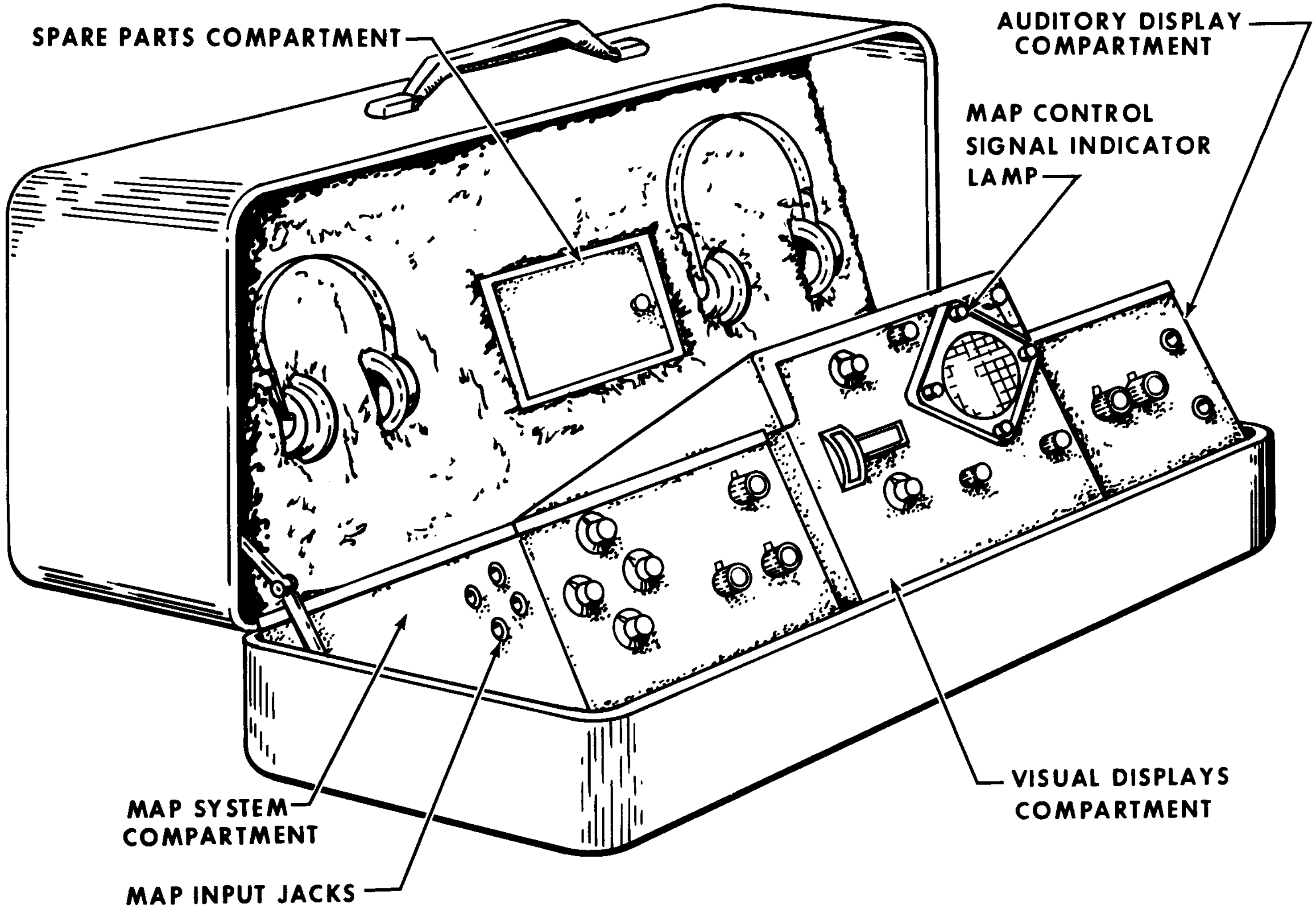

Figure 4. Sketch of ultra-quick control-display device.

MAP SIGNAL PICK-UP AND PROCESSING

The MAP signals are detected from the operator's musculature via a set of specially designed electrodes. Three surface electrodes are utilized to detect each muscle group response differentially to minimize noise and 60 cycle interference. Each tracking axis is controlled by two muscle groups, i.e., one muscle group controls half the display axis.

The MAP signals controlling each half axis have individual processing circuits. The processing circuits, which are based upon a design by Antonelli and Waring[1], consist of a differential amplifier, several stages of power amplification, and a Schmidt trigger mounted on printed circuit cards (see Figure 5 and Appendix A). The outputs of the Schmidt triggers from complimentary circuit cards are fed differentially into a Philbrick Model P45AU solid state operational amplifier. This amplifier determines whether the output from that particular channel will be 0, +10v or - 10v DC. One muscle group controls the positive, the other the negative half of the axis while simultaneous contraction of opposing muscles results in zero output (see Appendix A).

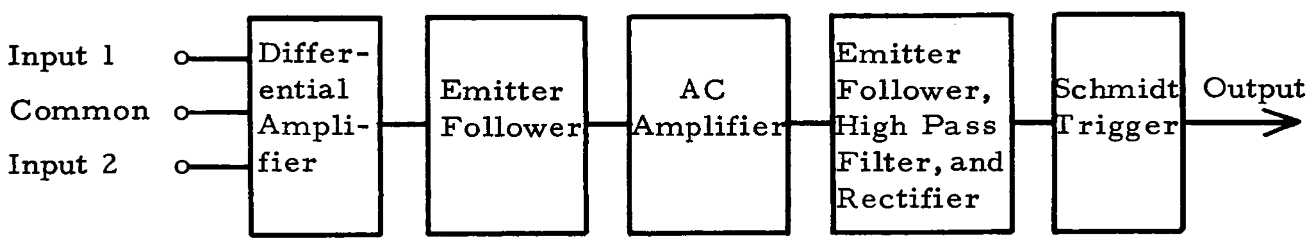

Figure 5. Block diagram of a MAP circuit card.

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[1] Antonelli, D.J. and Waring, W. Circuit for a one degree of freedom myoelectric control. Medical Research Engineering, in press.

As an alternative to the normal three state output in each axis, the device has a continuous output which is produced by a single integration of each axis of control signal. The integrations for continuous output are performed by a pair of Philbrick P85AU solid state amplifiers.

VISUAL DISPLAY

The tracking inputs are displayed by either an extensively modified EICO Model IO-10 3" CRO or a pair of 1 - 1/2" zero-center side-mounted meters (see Figure 4). The scope display is mounted in the center of the control-display console with the face at approximately a 65° angle with reference to the horizontal plane. If 110v AC is not readily available for the CRO or if otherwise desired, the two 1-1/2" meters mounted on the control-display console permit meter display of each axis. However, it is emphasized that the control loop is tighter with the CRO display, since meter displays have inherent inertial lags.

Four miniature lights mounted around the scope are provided to indicate when the bioamplifiers are providing a control signal. These lights provide immediate feedback of MAP control activation and are especially useful during MAP control training.

AUDITORY DISPLAY

The tracking error in each axis is also displayed via a set of Sony Model DR-3C(L) stereophonic earphones. The vertical axis error is displayed binaurally as varying pitch cursor tone (220 - 880 Hz), periodically interrupted by a fixed frequency reference tone (440 Hz). Rate of interruption is set at 5Hz with a reference tone on-time of 1/4 of the period, i.e., the reference tone is on for 50 ms then the variable tone is on for 150 ms. The horizontal axis error is displayed as the difference in loudness between the two ears. The loudness of the total frequency signal to the two ears ranges from zero to an adjustable maximum intensity; when no sound is heard in one ear (zero intensity), the other earphone displays maximum loudness. The operator's task is to null the error in each axis via frequency matching in the vertical axis and loudness matching in the horizontal axis. Appendix B contains a schematic diagram and parts list for the auditory circuit.

THE CONTROL CONSOLE

Figure 4 illustrates that the control console is functionally divided into three control panels: MAP, visual, and auditory control panels. The MAP control panel consists of three selector switches and four ganged potentiometers. The main selector switch (at the upper right of the MAP panel) in addition to having on, off, and battery charge positions, controls the inputs to the CRO. These inputs include the following:

- the amplified MAP signals,
- the output from the Schmidt trigger,
- an integrated (continuous) output from the trigger, and
- the external tracking system's input to the device.

Display of amplified MAP signals facilitates electrode placement, whereas display of Schmidt trigger signals permits observation of controller output. The selector switch directly below the main switch selects the channel of the MAP signal output that will be displayed on the CRO when the main switch is in the MAP signal display position. To the left of that control is a switch which is used to select either the bang-bang (discrete) or continuous output. The four ganged potentiometers to the far left of the MAP panel control the amplifier gain and the Schmidt trigger sensitivity for each channel of MAP.

The center or visual display control panel has clustered around the scope controls for focus, intensity, and vertical-horizontal centering. To the left of these controls are the vertical and horizontal gain controls. In addition to these panel controls, astigmatic, DC balance, and sweep centering controls are mounted on the scope chassis behind the operator panels.

The two auditory display controls mounted on the far right panel are used to adjust the loudness level for each phone and the loudness balance between phones. On the right side of the auditory control panel and out of reach of the operator, are several potentiometers which permit changes in the reference tone frequency, in the slope of the input signal/display signal frequency relationship, and in the slope of the input signal/binaural intensity difference relationship.

The four jacks mounted on the left side of the device are for the MAP electrodes from each muscle group. The external tracking system input and device output jacks are mounted on the right side of the device. The audio output jacks are on the auditory display control panel.

POWER SUPPLY AND BATTERY CHARGER

Power is supplied to the entire device by two sources: (1) An external 110v AC source that supplies the CRO and battery charger, and (2) Eight nickle-cadmium rechargeable batteries:

1 at + 14.4v

1 at - 14.4v

4 at + 12v (center tapped)

1 at + 6v

1 at - 6v

The battery power is sufficient for 20+ hours of continuous operation before recharging is required. The battery charger requires 110v AC power and consists of a full wave rectifier and voltage dividing circuit which supplies the batteries at their appropriate voltage and charge current. The battery charger is designed so that overnight continuous operation will fully charge the batteries.

SPARE PARTS

Two Philbrick operational amplifiers, one MAP circuit card, and a set of audio circuit cards are supplied with the device as spare parts. Spare parts are housed in the upper shell of the carrying case.

SECTION IV

PRELIMINARY DEVICE EVALUATION

PRELIMINARY DEVICE EVALUATION

The primary purpose for development of the MAP control device was to demonstrate the increase in operator response speed, frequency, and flexibility that accrues from the use of advanced manual control techniques. The reaction time study reported in Section II attested to the increase in operator response speed that is possible with MAP control and simultaneous visual-auditory display. The present study was concerned with evaluation of the developed MAP control, visual-auditory display device in a manual control context.

On the basis of the results of the reaction time study, it was expected that the developed device would substantially increase operator bandwidth in a manual control situation. Also suggested by the previous work was the possibility that the MAP control system could be operated by muscle groups other than those of the limbs and thereby free the operator's limbs for other control activities. The present study is concerned with a preliminary demonstration of these two points.

Briefly, the device was evaluated in a one-axis acceleration tracking situation. Two conventional control-display configurations were compared to the developed control-display device. The tracking system employed was an adaptive or self-adjusting forcing function frequency system. The five sine waves comprising the forcing function were automatically speeded up or slowed down in unison to keep the operator tracking at a preselected criterion level. When operator error was greater than criterion, the forcing function frequency decreased; when error was less than criterion, the forcing function frequency increased. In this way operator error was kept constant and the dependent variable became the forcing function frequency (expressed as a per cent of its maximum) that the operator could control within the fixed criterion of error. The independent variables of the study were forcing function amplitude and control type. The experimental design consisted of a comparison of three controllers in terms of maximum forcing function frequency controllable across a range of forcing function amplitudes.

It is emphasized that these data are preliminary and were collected under less than ideal conditions. These data represent the performance of one subject who though familiar with the tracking system had little experience with MAP control. The control-display device itself was not functioning as expected and required tuning adjustments between data collection runs. Also, the MAP control signals were not reliable, i.e., the subject was often required to repeat his control activity to properly activate the device. Probably the most important limitation on these data was that the tracking system imposed an artificial ceiling on the MAP scores. Nevertheless, these data do suggest the outcome that is expected in the latter more controlled evaluation.

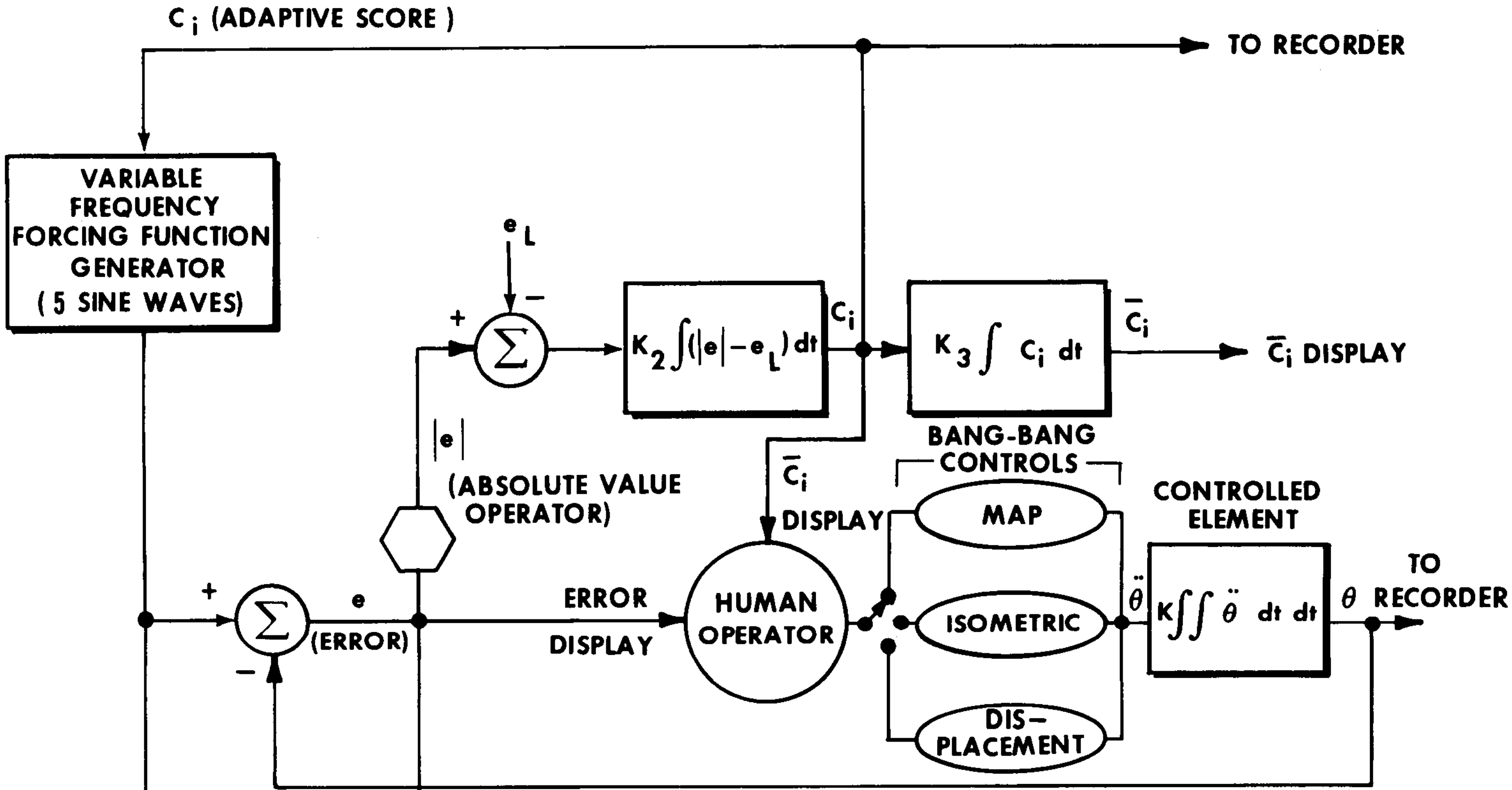
METHOD

Apparatus

The evaluation equipment consisted of: (a) the adaptive frequency, acceleration tracking system, (b) two conventional control-display configurations and the MAP control device. Figure 6 schematically represents the entire evaluation layout.

The display for the three control-display configurations was a compensatory visual display, the 3" cathode ray oscilloscope (CRO) incorporated in the developed device. The error signal was displayed as movement of a small spot in the horizontal axis. The subject's (S's) task was to null the error, i.e., to center that spot on the scope. The three controls were: (a) a conventional displacement joystick, (b) a physically similar isometric control, and (c) MAP control picked-up from the S's left and right cheeks. All three controls required compensatory control activity in the horizontal dimension: in the case of displacement control, movement; with isometric control, force; and with MAP control, cheeks muscle activation (see Appendix C). In each case the control output was a fixed amplitude discrete on-off-zero (bang-bang) signal.

The forcing function consisted of the sum of five inharmonic sine waves of equal amplitude, proportionately spaced in the decade between .025 and .25 cps at maximum value. The adaptive circuit automatically adjusted the "per cent of maximum" forcing function frequency displayed to the operator, thus at a 50 per cent score, forcing function frequency would range from .0125 to .125 cps. The amplitude of the forcing function was adjustable to a maximum of 100% of the display scale, e.g., if the forcing function amplitude was set at 90%, the maximum that the forcing function could displace the displayed error signal was 90% of the display scale. The error criterion was set at 10 per cent of the display scale. Whenever error exceeded this amount, the forcing function decreased in frequency and vice versa.



LEGEND:

SELF ADJUST SCORE, $C_i = K\int(|e|-e_L)\,dt$

WHERE, K= CONSTANT

e = ERROR

e_L= ERROR CRITERION

θ = CONTROLLER OUTPUT

$\bar{C}_i$ = MEAN FORCING FUNCTION FREQUENCY

Figure 6. Schematic of the evaluation system.

The recording equipment consisted of meters that displayed to the experimenter, (a) the instantaneous per cent forcing function being controlled, and (b) the integrated or mean forcing function frequency controlled during a run. In addition to the meters, an X-Y recorder was employed to plot a time history of the instantaneous forcing function frequency tracked. The data discussed herein will only be concerned with the mean forcing function frequency controlled during a data run.

Procedure

One male college graduate was employed as the S in this preliminary evaluation. The S was familiar with the self-adjust feature of the tracking system and had considerable experience in acceleration tracking with both displacement and isometric controls. His experience with MAP control via the cheek muscles was quite limited, totaling perhaps one hour of sporadic tracking.

The experimental design required S to track for 3 min with each controller at forcing function frequency amplitudes of 60, 70, 80, 90 and 100% of maximum amplitude. In all, fifteen, 3 min tracking runs were required to complete the design. During the short rest period after each 3 min run the S received performance feedback. Shortly after completion of all the runs, the entire design was replicated. The order of the runs in the basic design was systematically varied to balance out learning and fatigue effects.

RESULTS AND DISCUSSION

Figures 7, 8 and 9 indicate that: (a) for all three controllers, as the maximum amplitude of the forcing function increased, the maximum controllable forcing function frequency decreases, and (b) MAP cheek control was consistently superior to either displacement or isometric control. Considering the less than optimal conditions of data collection, these results are quite encouraging.

Figure 7 depicts the first run through the experimental conditions. Comparing this figure with Figure 8, the replication of the basic design, several things become evident. Most apparent is that the S's performance significantly improved after the first experimental exposure. This improvement resulted in less of a performance difference between the displacement and isometric controllers and a greater difference between those two controllers and the MAP controller. That is, with experience, the advantage of the MAP cheek control over the other two controls became more evident.

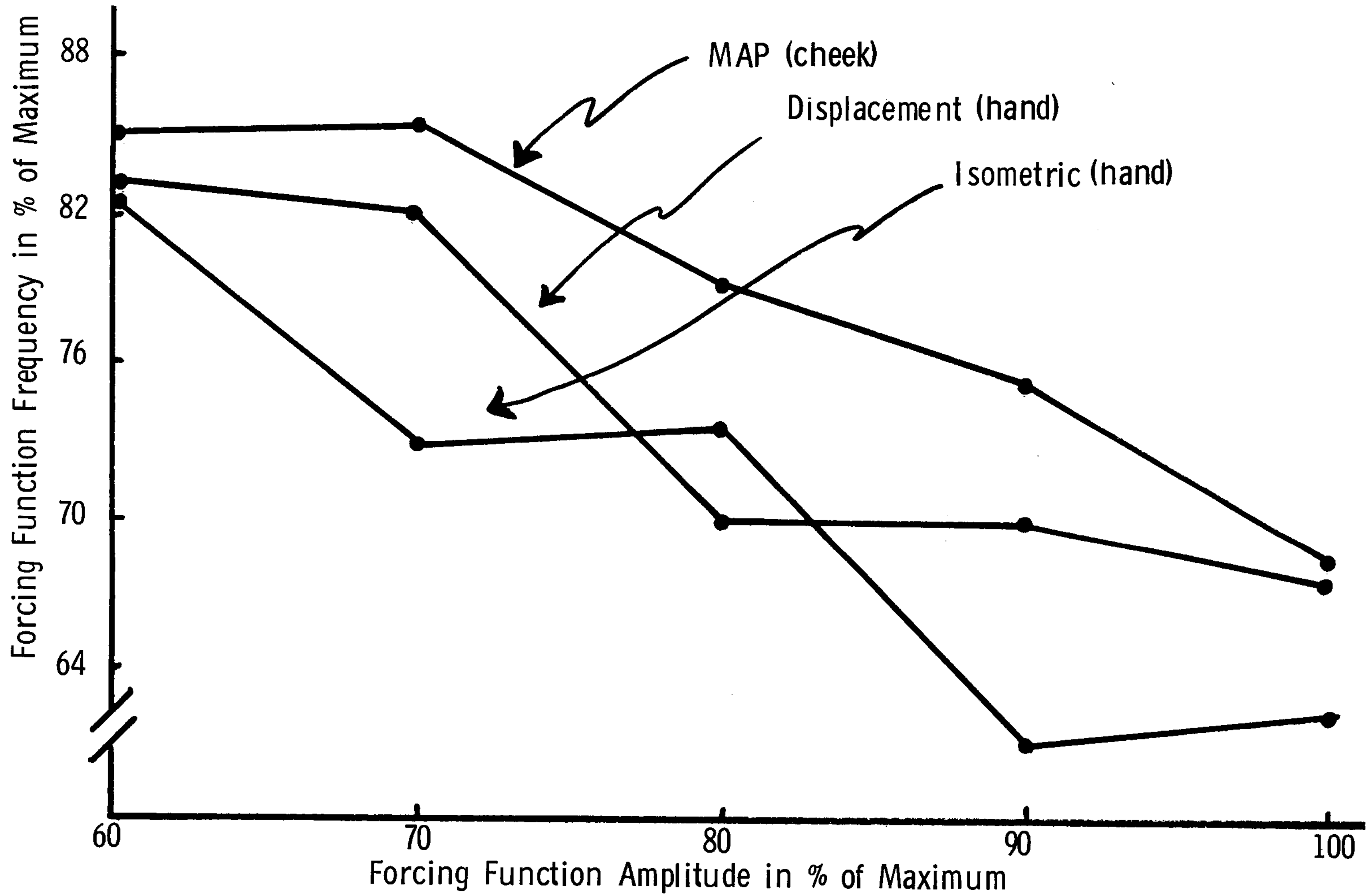


Figure 7. Maximum controllable frequency across forcing function amplitudes for the first experimental session.

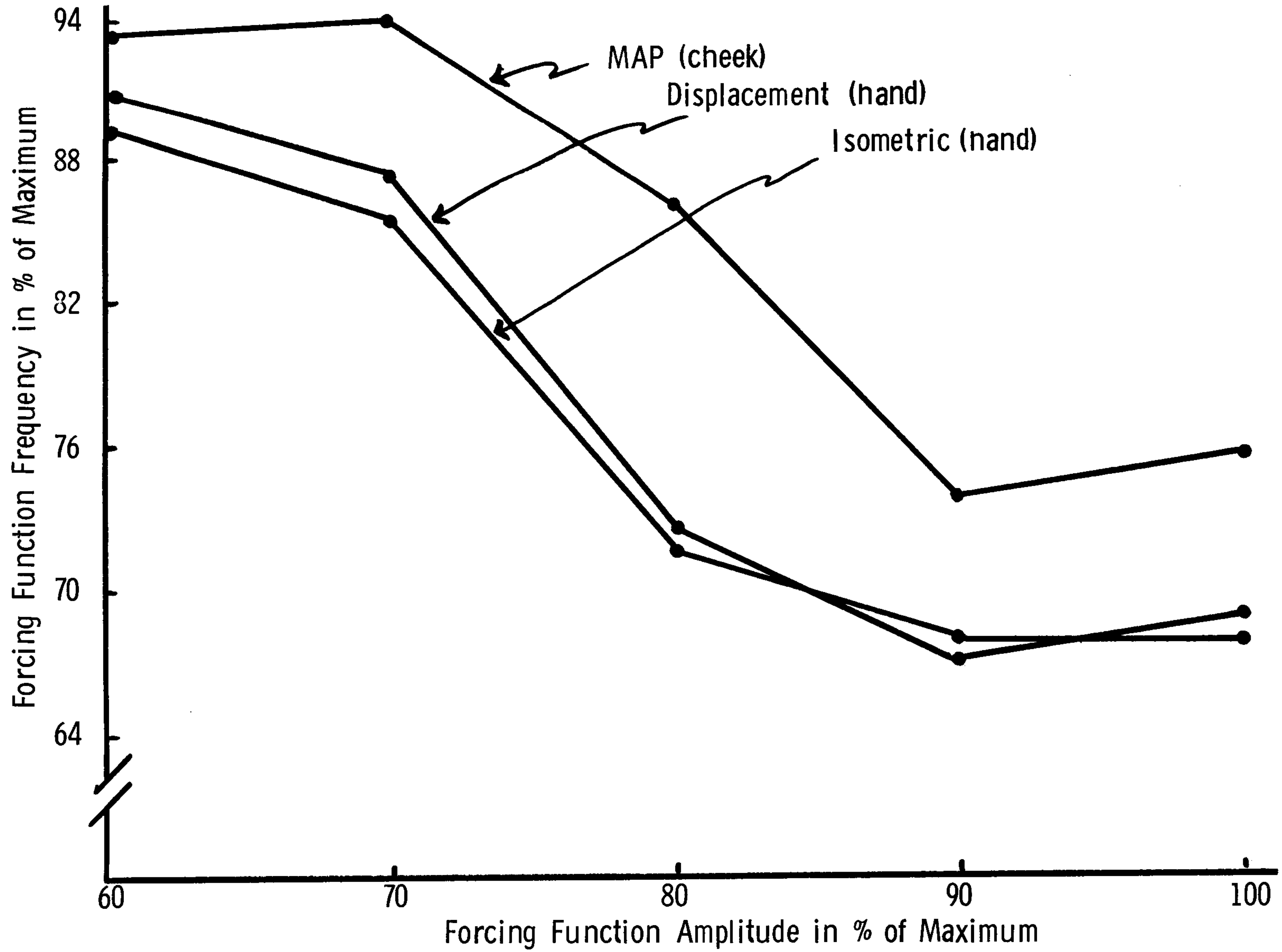


Figure 8. Maximum controllable frequency across forcing function amplitudes for the replication.

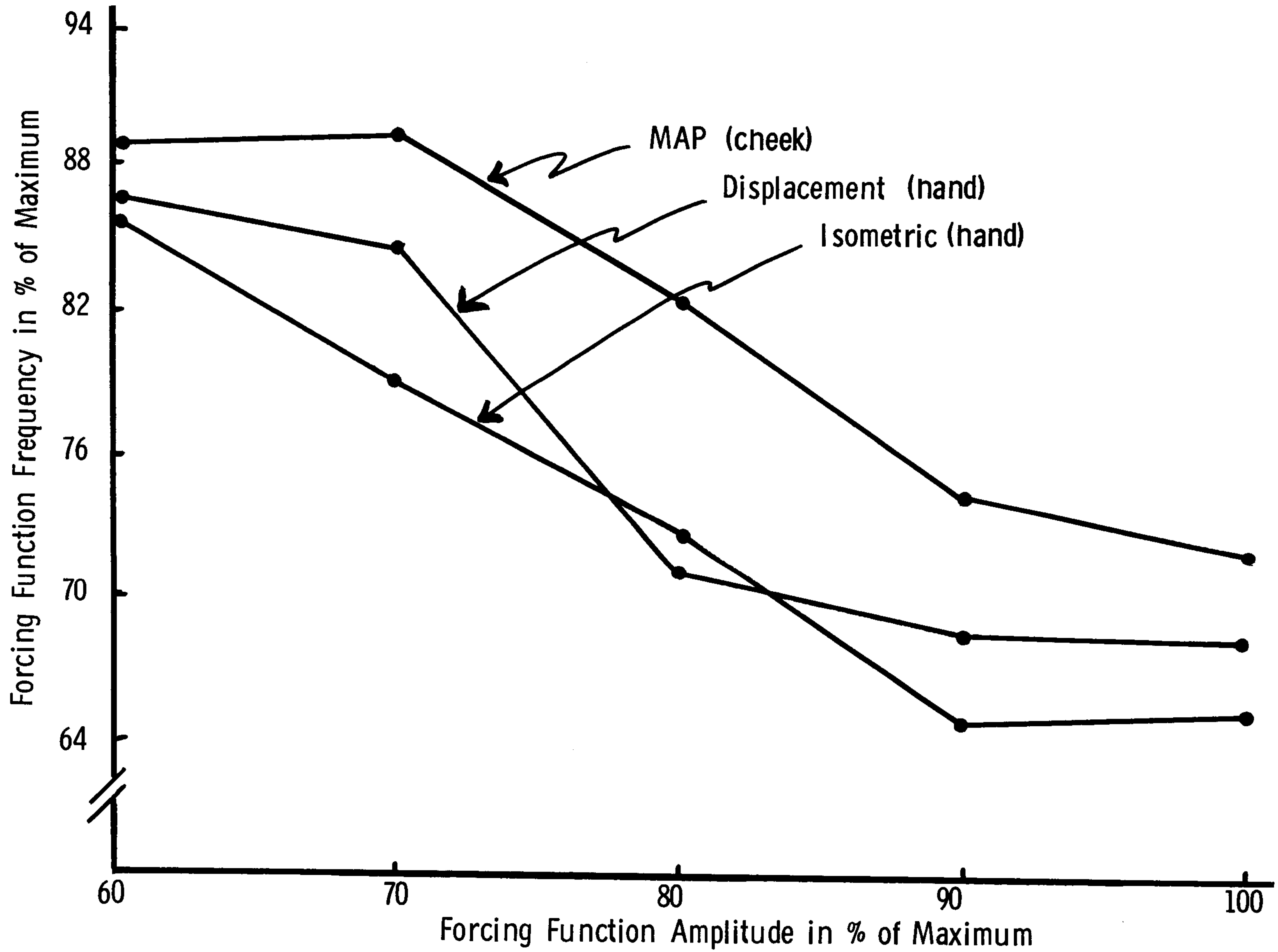


Figure 9. Mean maximum controllable frequency across forcing function amplitude for both experimental runs.

Figure 9 illustrates the mean forcing function frequency controllable under each of the forcing function amplitude conditions. Each point in this curve represents the arithmetic average of the S's score on each run through the experimental conditions. Because of the distinct difference in performance between the original run and the replication, Figure 8 rather than Figure 9 is probably more indicative of the actual differences between controllers. On the basis of the replication, it appears that in the final device evaluation, a significant increase in operator response frequency will accrue from use of the developed device.

The device as developed has, in addition to the visual display, an auditory display. On the basis of the reaction time study, it is expected that if simultaneous visual-auditory display were employed with the MAP controller, operator response frequency might increase more than suggested by these data. The effect of cross-modality display will be evaluated in a later study.

In relation to operator response flexibility, these data show that cheek MAP control not only is possible, but that it can be an improvement on more conventional hand controls. If these data are verified in later experimentation, the developed control-display device will have demonstrated the increased operator bandwidth and response flexibility that accrues from the use of advanced manual control technology.

CONCLUSIONS

Phase 1 of this project demonstrated that muscle action potential (MAP) control can increase human operator (a) response speed in discrete control situations, (b) response bandwidth in continuous control situations, and (c) response flexibility via MAP control by muscles other than those of the limbs. In addition to demonstrating MAP control feasibility, several other advanced manual control techniques were suggested for overcoming human operator response limitations in the manual control context. All of these techniques warrant further investigation, however Phase 2 of this project will focus on further development and evaluation of MAP control.

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APPENDIX A

MAP PROCESSING CIRCUIT DIAGRAMS

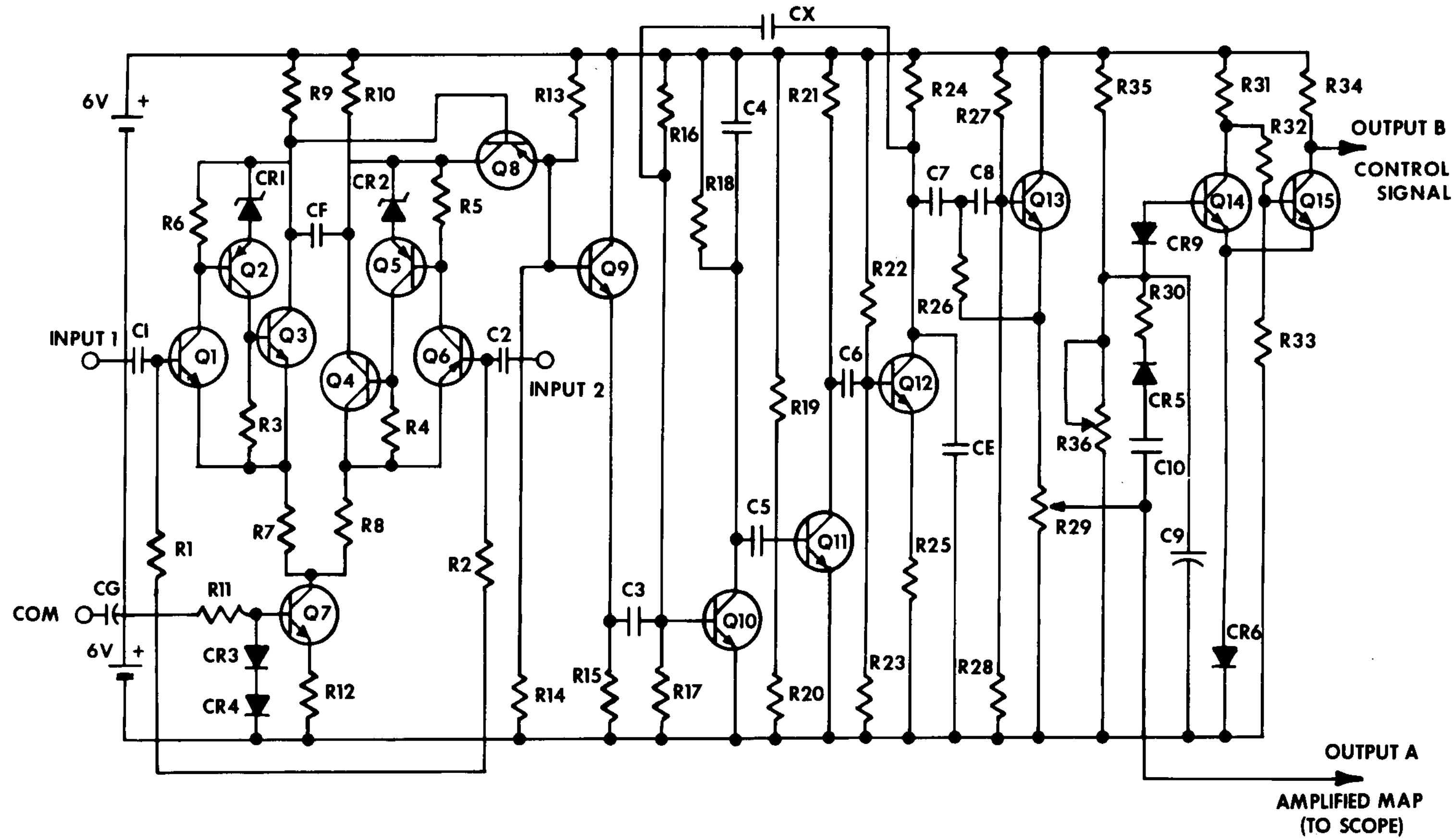

Figure A-1. MAP signal processing circuit card.

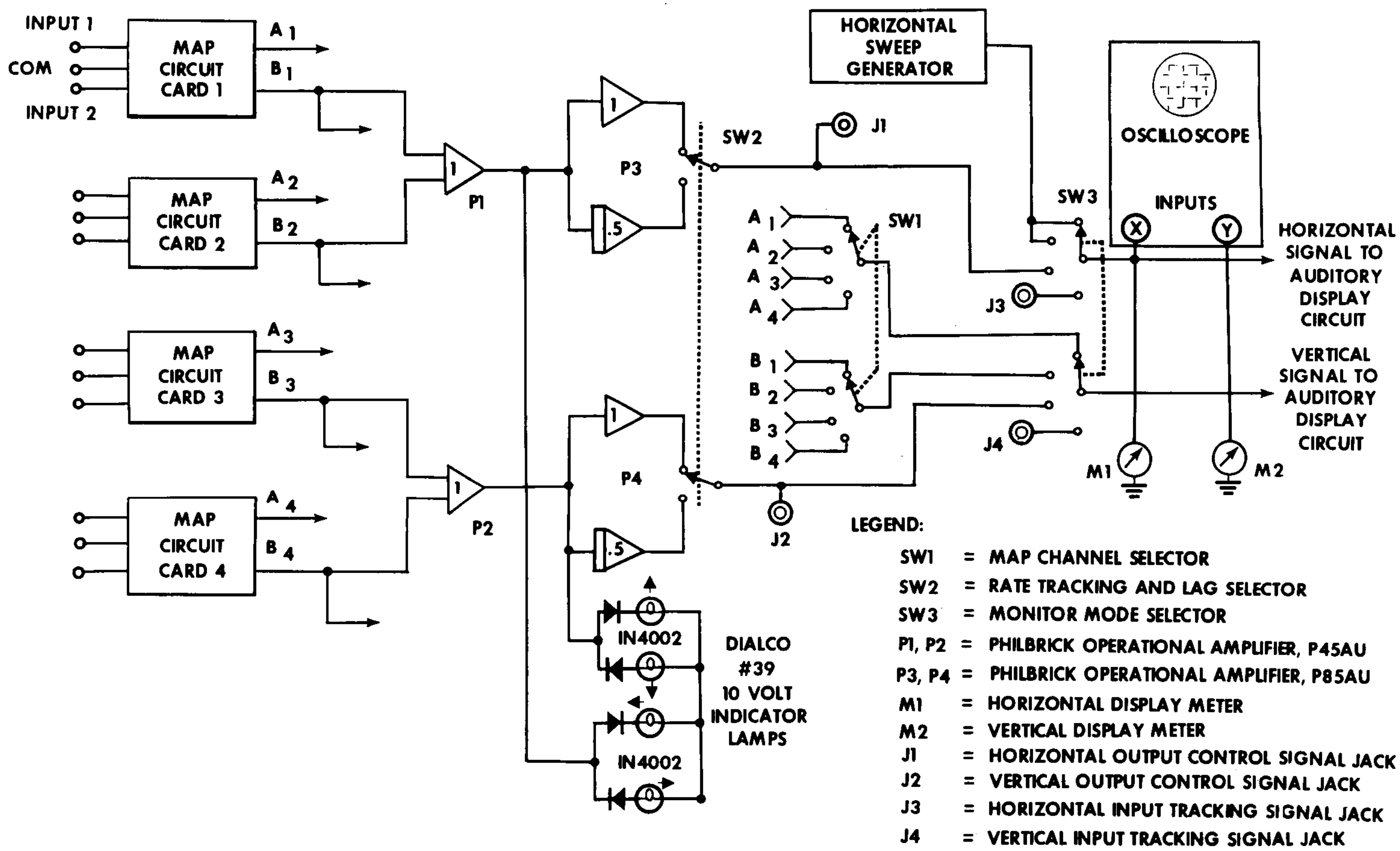

Figure A-2. MAP processing, control, and display circuits.

PARTS LIST FOR MYOAMPLIFIER CIRCUIT CARD

ITEM	NAME	DESCRIPTION
1	Q1, Q3, Q4, Q6, Q9, Q10, Q12, Q13, and Q14	Transistor, NPN 2N3565 Fairchild
2	Q2, Q5, and Q8	Transistor, PNP 2N3638A Fairchild
3	Q7, Q11, and Q15	Transistor, NPN 2N2923 G.E.
4	CR1 and CR2	Diode, Zener, 3-3V, IN746 Hoffman
5	CR3, CR4, CR6, CR9	Diode, Silicon, 750ma, 100V IN4002 Motorola
6	CR5	Diode, Germanium, IN294 Sylvania
7	C1, C2, C3, C4, C5, C6, C7 and C8	Capacitor, 0.15μf/150VDC Mylar V146XR-8 Aerovox
8	C9	Capacitor, 4μf/15V, Electrolytic TE-1151 Sprague
9	C10	Capacitor, 601D-D41845-6543 650μf/7.5V DC Sprague
10	CE and CX	Capacitor, .001μf/1000V Ceramic 851-000-X5FO-102K Erie
11	CF	Capacitor, .01μf/1000V Ceramic 1811-000-Z5UO-103M Erie
12	CG	Capacitor, 10μf/15V Electrolytic TE-1155 Sprague
13	R7 and R8	Resistor, 12 ohms, 1/4w, ± 5%
14	R12	Resistor, 180 ohms, 1/4w, ± 5%
15	R25	Resistor, 470 ohms, 1/4w, ± 5%
16	R30	Resistor, 1000 ohms, 1/4w, ± 5%

ITEM	NAME	DESCRIPTION
17	R9, R10, R26	Resistor, 1.2K ohms, 1/4w, ± 5%
18	R20	" 2.7K " " "
19	R18	" 4.7K " " "
20	R32	" 6.8K " " "
21	R33, R34	" 8.2K " " "
22	R15, R23	" 10K " " "
23	R11, R14	" 15K " " "
24	R27	" 18K " " "
25	R3, R4	" 27K " " "
26	R31	" 33K " " "
27	R24	" 39K " " "
28	R17, R19, R28	" 47K " " "
29	R13, R21	" 100K " " "
30	R5, R6, R22	" 150K " " "
31	R16	" 560K " " "
32	R1, R2	" 2.2M, 1/4w, ± 1% metal or carbon film
33	R35	Resistor, 3M ohms, 1/4w, ± 5%
34	R29, R36	5K potentiometer

APPENDIX B

CIRCUIT DIAGRAM FOR AUDITORY DISPLAY

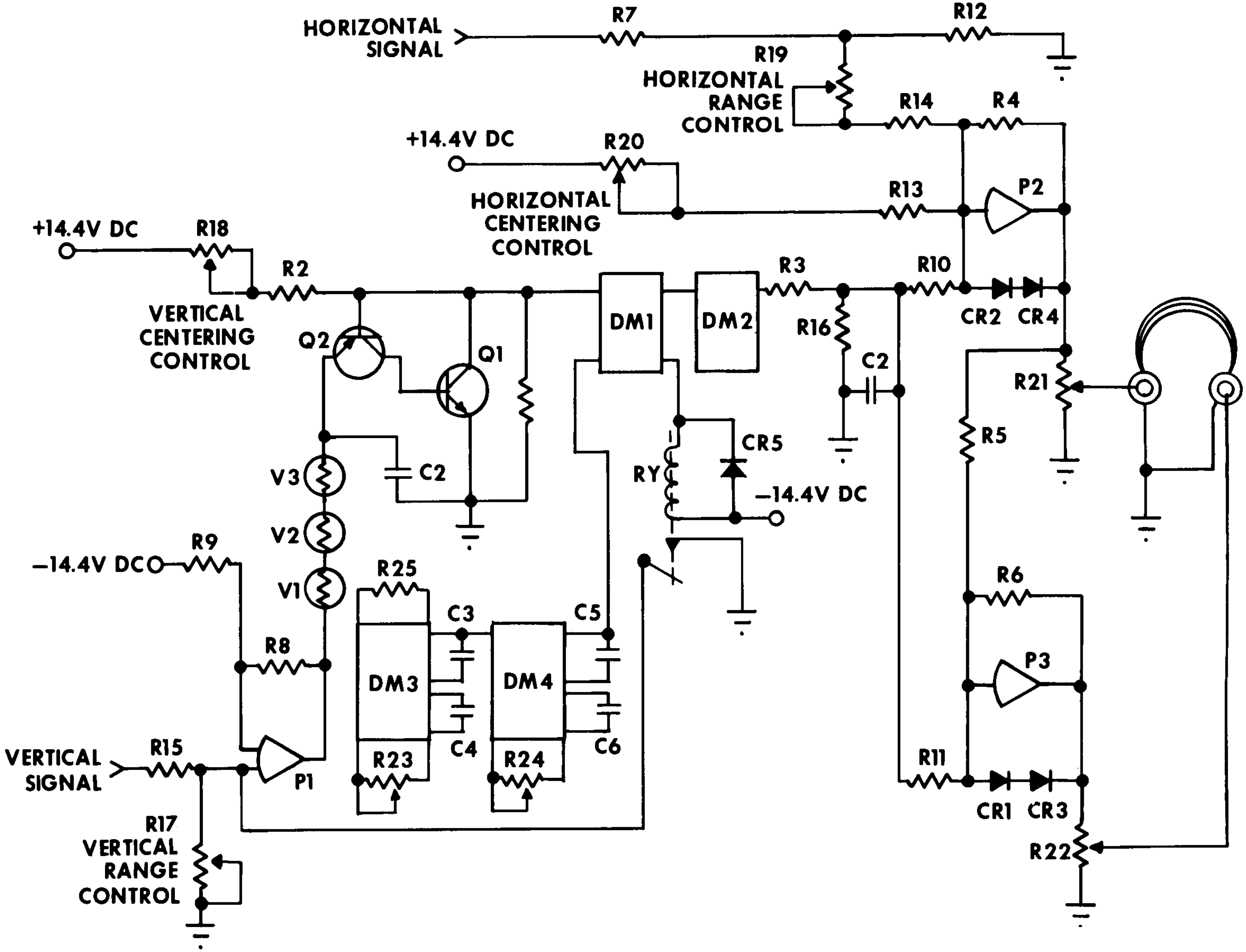

Figure B-1. Signal processing circuit for auditory display.

PARTS LIST FOR AUDITORY DISPLAY

ITEM	NAME	DESCRIPTION
1	V1	Veco Varistor 114 L_1
2	V2, V3	Veco Varistor 063h9
3	Q1	Transistor 2N 3567 Fairchild
4	Q2	Transistor 2N 3638 Fairchild
5	C1	Capacitor .01µf at 15V
6	C2	Capacitor .002µf at 15V
7	CR1, CR2, CR3, CR4	Diode IN4002 Motorola
8	R1	Resistor 5K ohms, 1/4w, ± 5%
9	R2	" 15K " " "
10	R3, R4, R5, R6, R7, R8	" 100K " " "
11	R9	" 167K " " "
12	R10, R11	" 220K " " "
13	R12	" 400K " " "
14	R13	" 850K " " "
15	R14	" 2M " " "
16	R15	" 5M " " "
17	R16	" 10M " " "
18	R17	Potentiometer, 100K ohms 2w ± 5%
19	R18	" 5K " " "
20	R19	" 2M " " "

ITEM	NAME	DESCRIPTION
21	R20	Potentiometer, 500K ohms 2w ± 5%
22	R21, R22	" 10K " " "
23	P1	Operational Amplifier, P85AU Philbrick
24	P2	" " " "
25	P3	" " " "
26	C3	Capacitor, 820 pf at 6v
27	C4	" 250µf at 6v
28	C5	" 30µf at 6v
29	C6	" 20µf at 6v
30	CR5	Diode, IN695
31	R25	Resistor, 1.5K ohms 1/4w ± 5%
32	R23, R24	Trimpots, 2K ohms 1/4w ± 5%
33	RY	Relay, MPR-1A Dunco
34	DM1	Relay Driver/Pulse Amp. EM5005M Electronic Module Corp.
35	DM2	Flip-Flop "D" EM5002 Electronic Module Corp.
36	DM3, DM4	Delay Multivibrator EM5011 Electronic Module Corp.

APPENDIX C

ELECTRODE FACE MASK DESCRIPTION

ELECTRODE FACE MASK DESCRIPTION

Figures C-1 and C-2 illustrate the electrode face mask that was developed after several commercial electrodes and electrode mounting techniques were determined to be impractical for MAP control. The mask as illustrated is designed for two axis control with the cheek muscles controlling one axis and the forehead and chin muscles controlling the other axis. Preliminary evaluation has indicated that when the mask is attached to the developed MAP control device a subject can, with training, control in two axes with minimum facial muscle movement, and can talk and smoke without inadvertently actuating the control device.

The mask is formed from 3/16" neoprene stock and is custom fitted to the operator. Nickle plated 1/2" diameter electrodes, three per muscle group, are embedded in the mask. The electrodes penetrate the mask and are clipped to shielded leads on the outer surface of the neoprene. The electrodes can be easily unclipped from the leads and moved to other locations. Further development of the mask is required; however at present the design offers the following advantages:

- excellent contact to the skin without the use of electrode jelly;
- easy electrode attachment, removal, replacement, relocation; and
- nearly exact positioning of the electrodes with each donning.

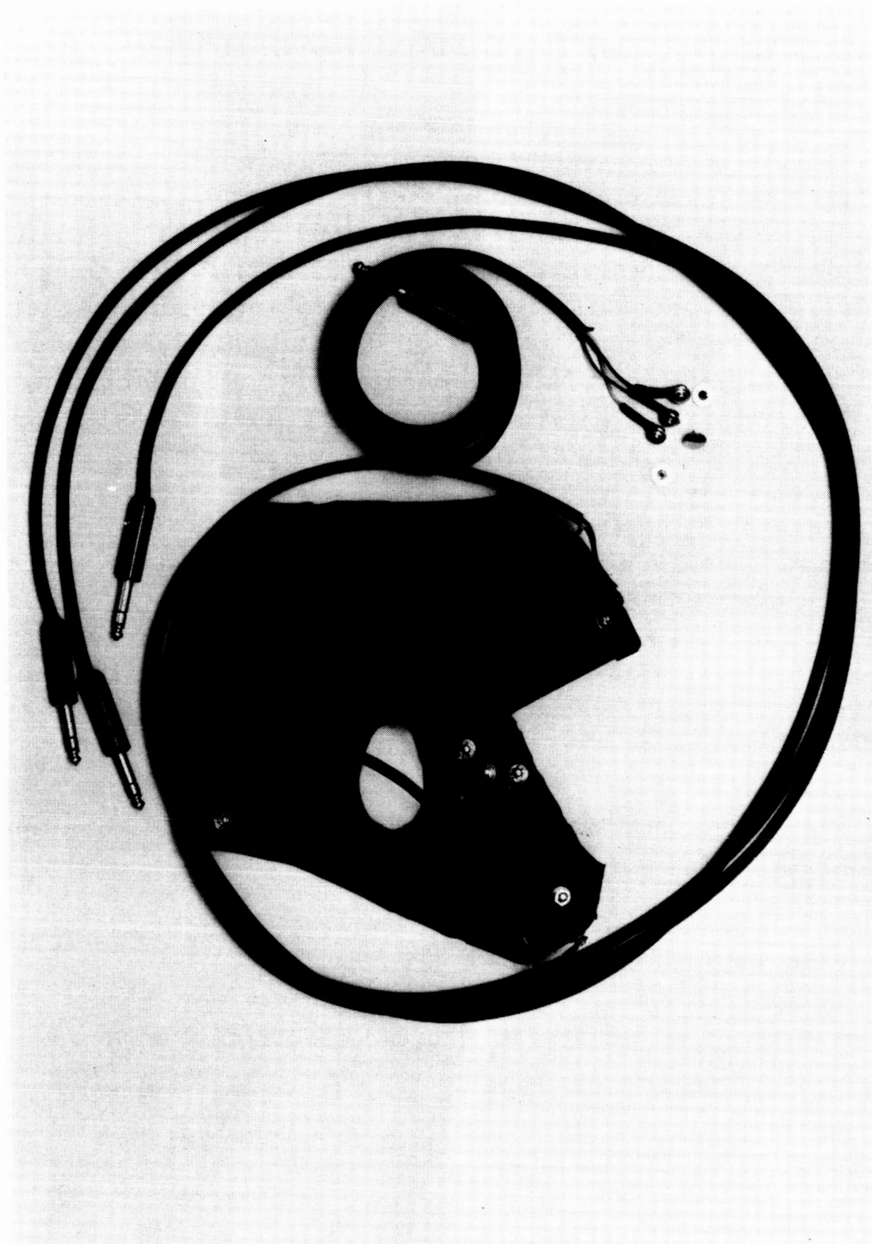

Figure C-1. Neoprene face mask for positioning MAP electrodes, showing disassembled electrodes in one axis.

24-HOUR PROTECTION

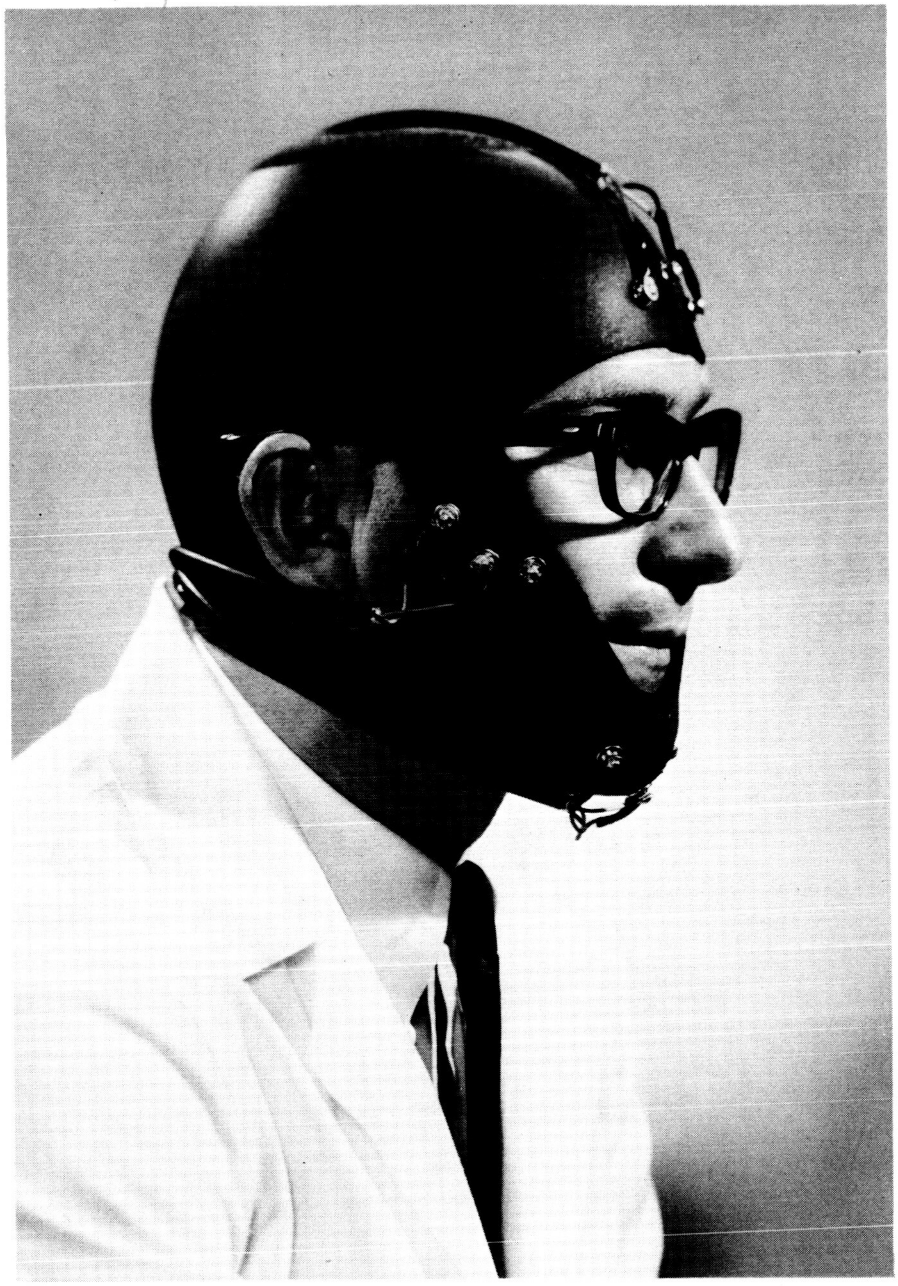

Figure C-2. Neoprene face mask for positioning MAP electrodes, as employed in two-axis MAP control.

NASA-Langley, 1967 —— 5 CR-874